4.0 Strategic Technology Areas

Updated 2001

In the previous section, the five Strategic Enterprises described their technology goals and needs in the context of their future missions. These mission-pull needs serve as the basis for the technology programs that are funded and managed by each of the Enterprises. However, as discussed in section 2.2, there is a need to ensure that NASA as a whole is providing sufficient support for a select group of very advanced technologies that offer the promise of revolutionizing how NASA does business in the future. These Strategic Technology Areas were identified by the Chief Technologist in cooperation with the Enterprises. They have been endorsed by the Technology Leadership Council and have been reviewed by the NASA Advisory Council.

Strategic Technology Areas
Advanced Miniaturization
Intelligent Systems
Compact Sensors and Instruments
Self-Sustaining Human Support
Deep Space Systems

In each case, these technologies include thought-provoking visions of future capabilities that could influence how NASA approaches a variety of its future activities. These technologies are not programs or line items in the NASA budget, but they serve as the technology-push in the annual process for developing the technology budget that was briefly described in section 2. They also represent ideal opportunities for cooperative programs with university researchers, drawing on the innovation and expertise characteristic of the academic community. These technology areas will be revalidated on an annual basis, and it is assumed that they will change over a period of time.

A report, *Space Technology for the New Century*, by the National Research Council (NRC) identified a group of high-risk, high-payoff key technologies, and it recommended a sustained level of research and technology funding for these areas. While there is not a one-for-one correspondence with the NASA Strategic Technology Areas, the two lists are closely related. Nearly all of the NRC technology areas are included in the Strategic Technology Areas and, in some instances, are needed to support goals associated with two or more Strategic Technology Areas.

4.1 Advanced Miniaturization

Updated 2001

The miniaturization of electronics and related components over the past decade has stimulated dramatic reductions in spacecraft size, while simultaneously producing tremendous increases in spacecraft capability. With the costs associated with spacecraft resources (mass, power, and volume) hamstringing every mission, advanced miniaturization technologies offer new methods to reduce costs and boost mission success. To enable this requires that all capabilities in micro and nanoscale fabrication and in information technologies be integrated. As these efforts are continued and extended, new generations of NASA science and exploration missions will emerge.

The advances in electronics and computation will allow reconfigurable, autonomous, "thinking" spacecraft. Other miniaturization techniques, such as micro-electro-mechanical-systems (MEMS), photonics, and nano-engineering materials and devices, will enable the development of small sensor, communications, navigation, power, thermal, and propulsion subsystems with very low mass, volume, and power consumption that operate in the rigors of the space environment. These components, brought together into microsystems, will provide opportunities for entirely new space architectures, such as distributed networks of microprobes on planetary surfaces, nanorovers that drive, hop, fly, and burrow, and constellations of microspacecraft (fig. 4.1-1) that make simultaneous measurements and function as a sparse array for innovative remote-sensing applications.

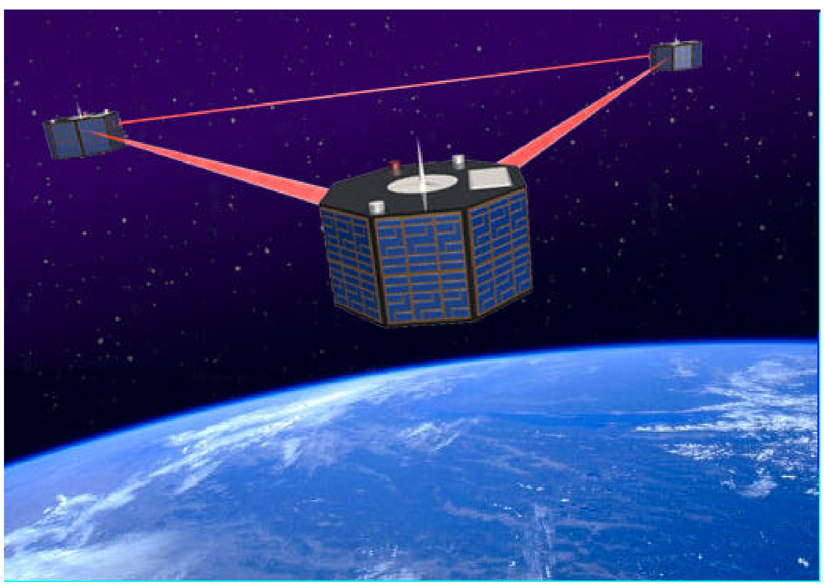


Figure 4.1-1. Depiction of the New Millennium ST-5 mission. Three miniature spacecraft - only 20 kg each - will fly in formation to demonstrate their ability to act as a single system, a precursor for NASA missions employing dozens of microspacecraft.

On conventional spacecraft, both robotic and crewed by humans, miniaturization technologies will dramatically reduce mass, volume, and power consumption, thus lowering launch costs and providing new capabilities for science and human support. The same benefits apply to applications in aeronautics and space transportation systems.

Another significant benefit of miniaturization technologies is the ability to increase mission reliability and safety. Smaller microsystems are inherently less susceptible to shock; microsystems' reduced power needs permit distributed, more robust power generation, storage and control; and the implementation of redundancy in the system is greatly enabled. New methods of creating electronic circuitry, such as nanoparticle-based non-volatile memory, which is radiation hard and operates over wide temperature extremes, will allow spacecraft to function for long durations in harsh environements. Finally, the capabilities of integrating swarms of sensor nodes into an aero or space system, made possible through increasing miniaturization, will give those vehicles the ability to constantly and completely monitor the vehicle's health status, and perhaps offer the vehicle the capability to "heal" itself.

Advanced miniaturization not only serves many different customers but also cuts across many technical areas and requires a multidisciplinary approach. These disciplines include physics, chemistry, biology, and electrical, mechanical, and aerospace engineering, which are applied to areas such as sensors, instruments, avionics, mechanisms, optics, robotics, propulsion power, communications, life sciences, life support, and space medicine.

Objective and Scope

The objective of the miniaturization thrust is to conduct research and development in technologies to enable new levels of miniaturization, integration, and power reduction in space and aeronautic systems. Thrust research and development—OR—The thrust of research and development encompasses methods for reducing the size, mass, and power consumption of spacecraft, microlanders, and instruments. (Reduced power consumption translates into mass reduction because a smaller power system is needed, and it can also be enabling in power-starved missions.) Research and development activities include design, analysis, fabrication, and test methods at the device and component levels. However, development areas also include new architectures and concepts for avionics, computational, communications, and space systems (such as microspacecraft and nanorovers) that are uniquely based on and enabled by miniaturization (e.g., MEMS, micro-optics, and nanotechnology). Miniaturizing components, together with new levels of architecture, systems integration, and advanced packaging, will enable these new concepts. Advanced microelectronics and photonics technologies are included in this area.

Aeronautics and space transportation systems also require mass, volume, and power reduction. In addition, they need new levels of vehicle health monitoring that can be enabled by embedded microsensors and new levels of computation to make smart systems. Note that aerospace systems are an application area in which advanced miniaturization activities require, or overlap with, discipline-level technologies not necessarily encompassed by other strategic technology thrusts. The miniaturization thrust will conduct research and development to ensure that the devices and microsystems will function in the harsh environment of space, which includes temperature extremes and radiation. Activities included in the advanced miniaturization thrust are listed in Table 4.1-1.

TABLE 4.1-1. Advanced Miniaturization Areas

Micro and Nano Devices	**Micro-Electro-Mechanical Systems (MEMS)**
Micro- and nanoelectronics	2D and 3D Micromachining techniques
Photonics	MEMS sensors (physical, chemical and biological)
Superconductivity	MEMS actuators
Micromagnetics	Micro-optics and optoelectronics
Bandgap engineering in low dimensional structures	Radio frequency components
Detector devices	Non-Silicon MEMS fabrication
Device physics and modeling	Integration and packaging
Advanced materials	Space environmental compatibility
Material and device fabrication and characterization	Extensions into nano-electro-mechnical systems (NEMS)
Computation, Avionics, and Communications	**Microsystems**
Revolutionary computing (biological/DNA, quantum, single electron, and superconducting)	Systems on a chip
Neural networks	Mixed signal systems
Optical processing	Smart sensors
Scaleable, fault-tolerant flight computer	Architecture and systems analysis
Avionics sensors	Hybrid bonding and packaging
Low-power electronics	Reliability modeling
Radiation-resistant materials and architectures	Systems simulation and test
Innovative radiation shielding	Distributed networked microsystems
Wireless sensors and systems	Microspacecraft
Monolithic microwave integrated circuits	Microprobes
	Nanorovers and nanorobots
	Constellations and microprobe networks
	Vehicle health monitoring system

The miniaturization thrust will focus on the highest payoff technologies with a balance between technology-driven innovation and those serving the current established needs of NASA customers. Note that the NRC, in its report, has recommended increased investment in MEMS, radiation-resistant electronics, and wideband, high-data-rate communications.

Technical Approach

Micro- and Nanodevices. New micro- and nanoelectronics will enable quantum leaps in computing, communications, sensing, and signal processing. Advances will be accomplished by utilizing new nanoscale materials, nanometer lithography, novel self-assembly methods, and unprecedented degrees of integration to make extremely high-speed yet low-power devices. An example of these new capabilities is displayed in figure 4.1-2: a mixer, created by nanometer lithography, operating at terahertz frequencies, enabling new instruments for atmospheric study.

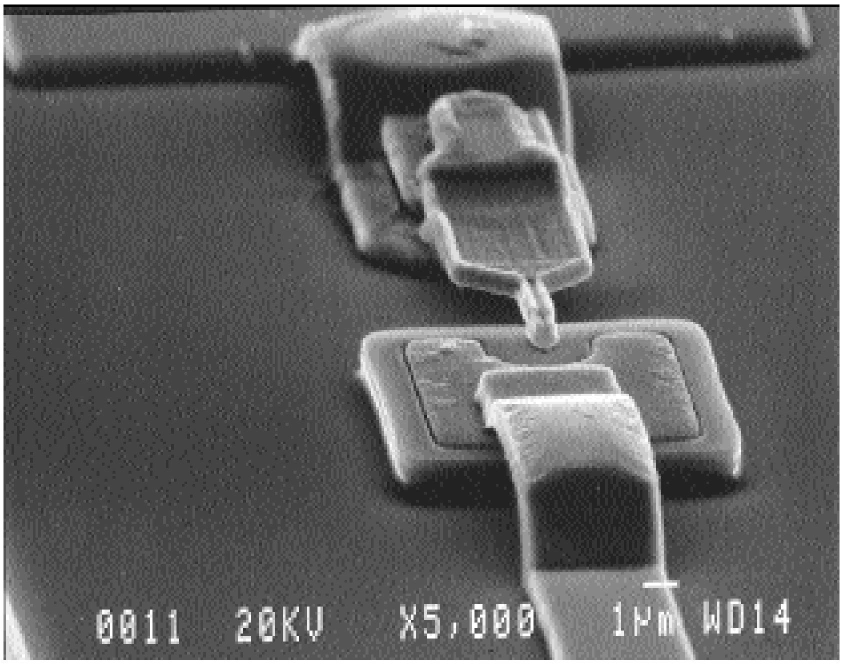


Figure 4.1-2. Monolithic 2.5-Terahertz Mixer Incorporating a 100-Nanometer Air-Bridged Gas Schottky Diode (The diode is being developed for the Earth Observing System Microwave Limb Sounder to measure oxygen-hydrogen emissions as part of a study of ozone chemistry in Earth's atmosphere.).

Photonics in space enables miniature science instruments, very high-speed optical communications, real-time optical processing, metrology, and life support systems through the use of semiconductor lasers and integrated optoelectronic devices made from new material systems and novel structures. Bandgap engineering achieved by molecular beam epitaxy and metal-organic vapor phase epitaxy (MOVPE) growth of III-V and silicon materials allows for a new family of heterostructure devices, such as quantum wells and quantum dots, that can be used as detectors in unique parts of the electromagnetic spectrum and for long wavelength semiconductor lasers for in situ sensing. Wide bandgap materials such as silicon carbon, gallium nitride, and diamond hold promise for high-temperature devices, high power electronics, chemical sensors, ultraviolet sensors, and blue-green and ultraviolet lasers for free-space optical communications. High power, high frequency solid state RF systems (e.g. radar and Ka band communications) will be enabled by these wide bandgap material systems.

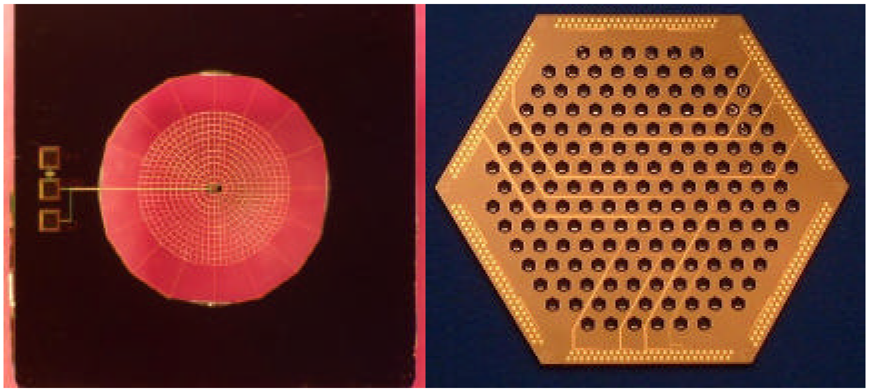


Figure 4.1-3. Silicon Micromesh Bolometers for Far Infrared Measurements. Versions of these detectors have provided vital information on the Cosmic Microwave Background. More advanced detector arrays will fly on the Herschel and Planck missions later this decade.

Superconductivity enables digital circuits operating up to hundreds of times faster than silicon while consuming much less power. Another key application for superconducting devices is as ultrasensitive detectors and focal planes. Heterodyne receivers based on superconducting mixers now operate at frequencies above one terahertz, with sensitivities approaching the quantum limit. Direct detectors and small focal planes are now being utilized in the far infrared, making precise measurements of cosmic microwave background (fig. 4.1-3). Research now underway points to the creation of detectors that have the capability of detecting and counting single photons, while resolving the energy and polarization of the photon. Reaching such a limit in performance enables maximum benefit from a telescope aperture.

Comprehensive understanding of the material and device physics combined into models and simulations will enable rapid design and optimization of electronic and photonic devices and systems. These models combined with experimental testing will reveal failure mechanisms and lead to highly reliable systems. Modeling, combined with advanced materials and device characterization techniques, including scanning tunneling, atomic force, scanning electron and transmission electron microscopy, photoemission, and electrical, thermal, and optical property measurements, will lead to dramatic progress in material and device development.

MEMS. MEMS enable orders-of-magnitude reductions in the size, mass, and power consumption of aerospace systems. Examples of MEMS devices include micromachined silicon gyros (fig. 4.1-4), accelerometers, seismometers, pressure sensors, valves, microthrusters, micropower sources, chemical and biological analysis systems, RF, optical and mechanical filters, and radio frequency switches. The vision for the future is of integrated MEMS Microsystems, micromachined from silicon, III-V compound semiconductors, glass, ceramics, metals, and plastics with several functions and fully integrated electronics. New hybrid bonding techniques will allow for three-dimensional microstructures of semiconductors, metals, insulators, and other materials to enable integrated optomechanical micro-instruments and miniature chemical analysis laboratories. MEMS-based actuators and motors will have the ability to provide sufficient force and torque to replace conventional mechanisms, and MEMS will be a key technology for microspacecraft, microprobes, and nanorovers. Smart skins with active control surfaces will be available for aircraft and launch vehicles.

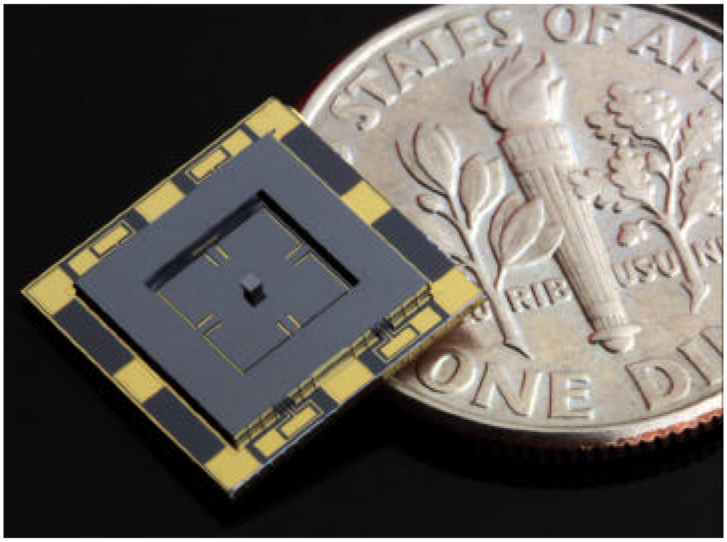


Figure 4.1-4. MEMS Fabricated Gyroscope: Shown is the resonant cloverleaf structure that is the heart of the device. Current versions now achieve drift rates of less than 1°/hr.

Micromachining techniques combined with electron beam lithography enable the surface of a material to be sculpted with a precision of 0.02 micrometer, which is a small fraction of the wavelength of light. Micro-optics in the form of analog surface relief diffractive optical elements enable compact high-performance optical instruments that cannot be realized using conventional optics techniques. Micro-optic gratings will enable new hyperspectral imaging spectrometers, holographic dispersers for imaging and optical processing, and lenslets for each pixel in a detector array. In figure 4.1-5, one such high-efficiency grating is pictured; this grating enables a hyperspectral imager to be the size of a soda can. Techniques such as deep reactive ion etching and LIGA allow real three-dimensional MEMS structures to be made. LIGA uses x-rays to make several millimeter-deep patterns in plexiglass into which metals can be electroplated. This opens up the MEMS area to metals that are used for gears, electromagnetic filters, and components for sensors such as mass spectrometers.

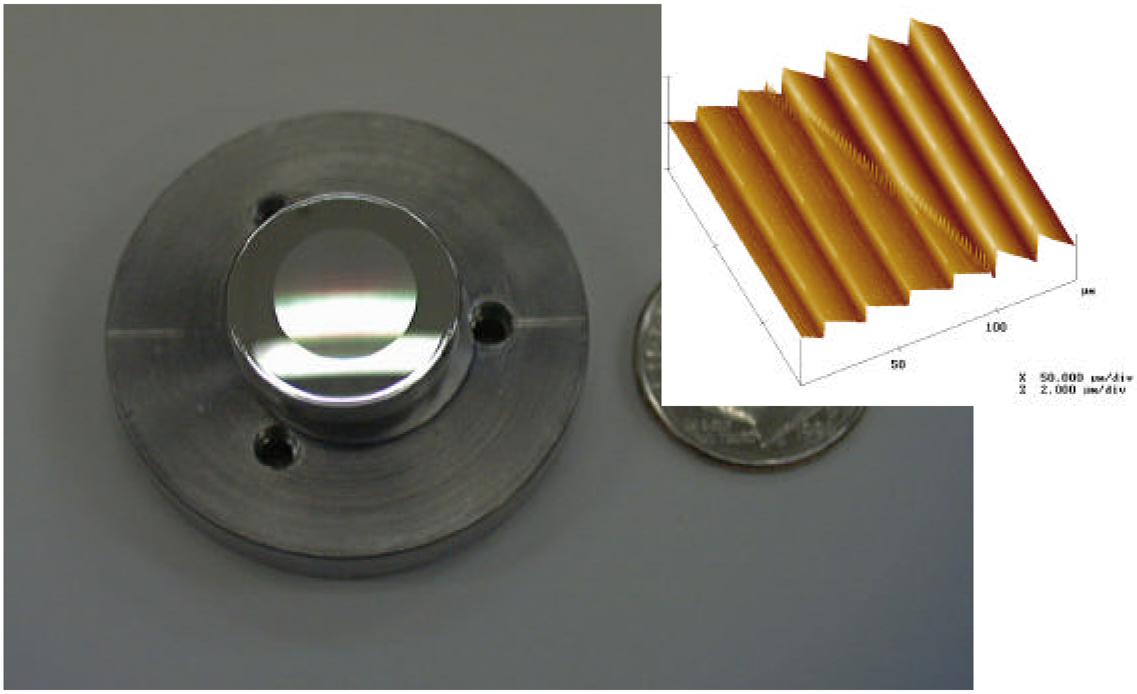


Figure 4.1-5. Dual-Blaze Micro-optic Grating Written With Electron Beam Lithography on a Convex Substrate. The inset picture shows an AFM image of the groove structure, with two different blaze angles.

A high-priority goal of the NASA Astrobiology program is understanding how life may have originated and persisted beyond Earth. Micro and nano fabrication techniques will be used to miniaturize bioanalytical devices to enable their use on Mars and Europa. These include miniature capillary electrophoresis systems, DNA detectors, and chemical sensors and biosensors for in situ investigations of biosignatures. Many of these require wet chemistry and sample preparation, and microfluidics will play a key role.

Nanotechnology and Biotechnology. The capability to design, grow, and fabricate materials at the nanometer level promises to have tremendous impact on space systems and instruments. Sensors based on nanoscale devices can offer high sensitivities for in situ detection of chemicals, down to single molecule detection. Quantum dot structures can be designed to be computing circuits, infrared detectors, biomolecule sensors, and solid-state lasers. Nano-materials, such as single walled carbon nanotubes (CNT), possess strength characteristics that may provide new limits of strengths; combined with CNT piezoelectric properties, active high strength structures will be investigated. CNT based electronics and sensors are also under development; atomic force microscopes incorporating a CNT tip have already been flight qualified for future Mars missions. (fig. 4.1-6). Carbon nanotubes offer unique electronic properties that may form the foundation for the post-silicon electronics world. From Nanowires in ultradense ICs to single electron transistors, and to novel memory storage elements, all are important topics for research to benefit the exploration of space.

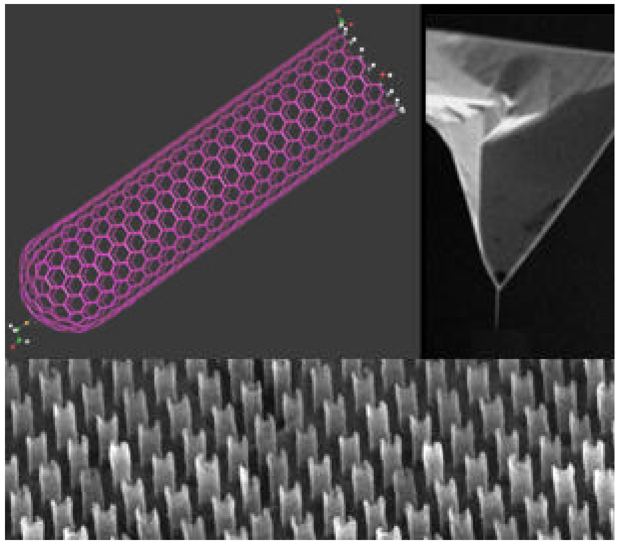


Figure 4.1-6. Carbon Nanotubes offer the potential to bring enormous advances in structural materials, sensors, and electronics. The single wall nanotube (shown in the upper left) can form a tip of an atomic force microscope (above right). Arrays of CNTs (bottom) will form the basis for cold cathodes, nanomechanical filters, and biomolecule sensors.

Of major emphasis for NASA over the next five years will be the production scale-up of carbon nanotubes; the development of carbon nanotube reinforced polymer matrix composites for structural applications; and the development of analysis, design and test methods to incorporate these materials into new vehicle concepts and validate their performance and life. However, NASA will also explore the use of other nanotubes such as boron nitride for high temperature applications, and research the use of crystalline nanotubes to ultimately exploit the full potential of these materials. NASA studies indicate that nanotube composites can reduce the weight of a reusable launch vehicle by a factor of two over the best composite systems today and by 80% over current aluminum structures. Early studies also indicate that the dry weight of a large commercial transport could similarly be reduced by about half, resulting in a fuel savings of about 25%. In the long-term, the ability to create materials and structures that are biologically inspired provides a unique opportunity to produce new classes of self-assembling material systems without the need to machine or process materials. Some unique characteristics anticipated from biomimetics ("mimicking" biology) include multifunctional material systems, hierarchical organization, adaptability, self healing/self-repair, and durability. This will allow tailoring the mechanical properties to meet the design requirements and revolutionize aerospace and spacecraft systems. Exploiting the characteristics of biological systems, new materials will enable the development of adaptable, self healing/self-repair, and durable structures.

Computation, Avionics, and Communications. Novel and revolutionary computing technologies will be pursued to leapfrog the "brute force" approach to prepare for the time (around the year 2010) when, according to the Semiconductor Industry Association Roadmap, the physical limits of feature-size reduction in silicon will be reached. Future computing technologies include optical processing, reconfigurable neural networks, single-electron, quantum, superconducting, and biological computing (fig. 4.1-7). Biological systems have inspired artificial neural networks, and biological systems outperform supercomputers in tasks such as pattern recognition, sensor fusion, real-time control, adaptation to the environment, and learning. Miniaturized, highly parallel electronic or optoelectronic artificial neural network processors will perform real-time onboard information processing for science, autonomy, and vehicle health management. Optical processors coupled with neural networks will control autonomous precision landing and docking and enable change detection to recognize new science opportunities and detect space system anomalies. The combination of optical sensors and advanced computation will result in a fully integrated “eye-brain” module of a “thinking spacecraft.”

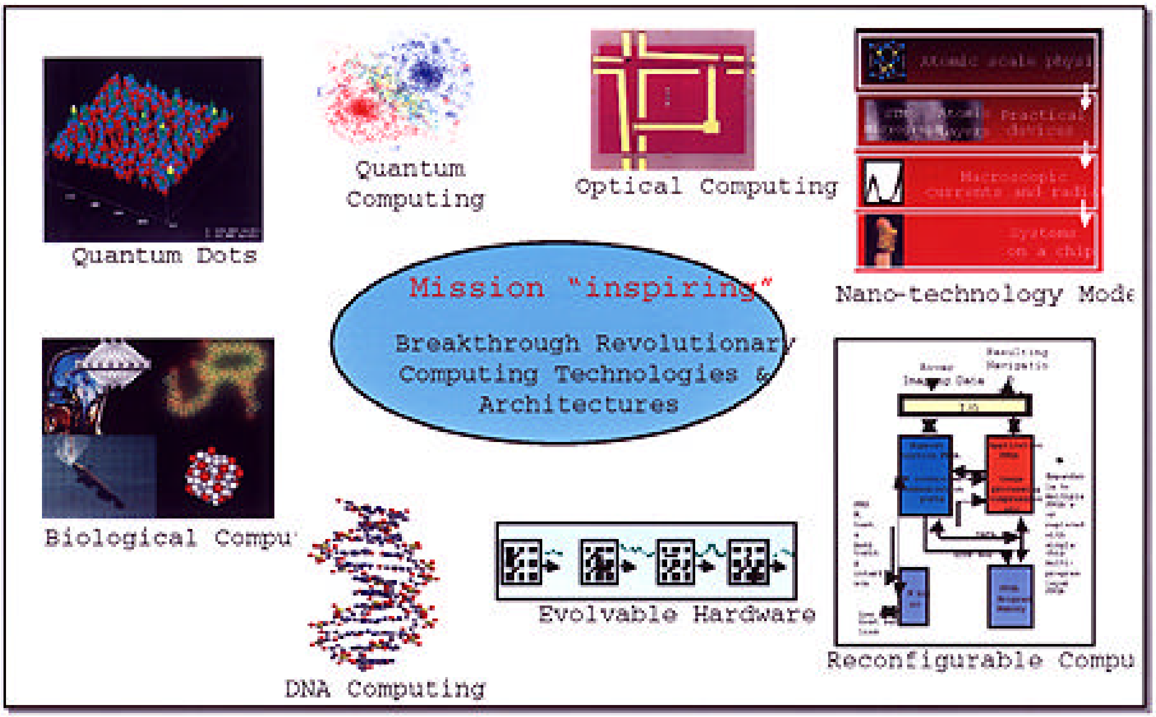


Figure 4.1-7. Examples of revolutionary computing technologies being pursued under the advanced miniaturization thrust.

Superconducting single-flux quantum logic will allow devices to operate at speeds many times that of semiconductors. Reconfigurable and evolvable hardware based on field programmable gate array technology will allow fully adaptive onboard computing. Quantum computers will be developed to solve intractable problems, and the potential of DNA computers will be evaluated.

High-frequency monolithic microwave integrated circuits (MMIC) will be pursued for their application to radar, millimeter, and submillimeter instruments and advanced communications systems. Performance and reliability modeling and simulation, coupled with system testing, will be used to rapidly converge on optimum designs. New low-power wireless communications technology will allow new levels of integrated sensor systems to monitor the health of rockets, spacecraft, and human space stations, as well as a network of science outposts on distant bodies. Miniature optical and radio frequency components will allow wideband, high-data-rate communications from anywhere in the solar system and beyond. These advances include digital radio frequency systems to increase stability and phased-array emitters for beam steering.

Future avionics architectures will be open and based on commercial standards with the goal of inserting commercial off-the-shelf technologies into space systems within 18 months of their ground-based introduction. Scaleable, high-performance, but low-power space computers using commercial laptop microprocessors will command the spacecraft and perform onboard autonomy calculations and science data analysis. The reliability needed by space missions will be provided by a combination of software-implemented fault-tolerance and radiation-resistant computer memories and electronics. New shielding techniques and protective materials, together with radiation-resistant electronics, will replace rad-hard parts in all but the most demanding applications. Miniaturized sensors such as accelerometers, gyros, and Global Positioning System (GPS) receivers will be integrated with flight computers into complete miniature avionics systems.

Microsystems. Systems on a chip will replace circuit boards with many discrete components, leading to much smaller and lower power systems with higher reliability. A current example is a digital camera on a chip that includes the imager, all-control electronics, and an analog-to-digital converter all on the same silicon chip. Future systems on a chip will include both digital and analog circuits, including power and radio communications. These mixed-signal applications present a significant challenge in system architecture, analysis, and packaging. Systems on a chip technology will enable highly capable, autonomous microspacecraft by integrating all electronic functions into a single monolithic unit. Complete propulsion systems for microspacecraft will take advantage of heterogeneous packaging of microelectronics, MEMS, and nanodevices (fig. 4.1-8). Low-power and wireless communications devices will be combined with sensors and imagers to eliminate wires and enable wireless networks of sensors for science on distant planets and for health management on aircraft, launch vehicles, and human space stations. Smart sensors and imagers will result in new applications, such as an optical communications acquisition and tracking system on a chip.

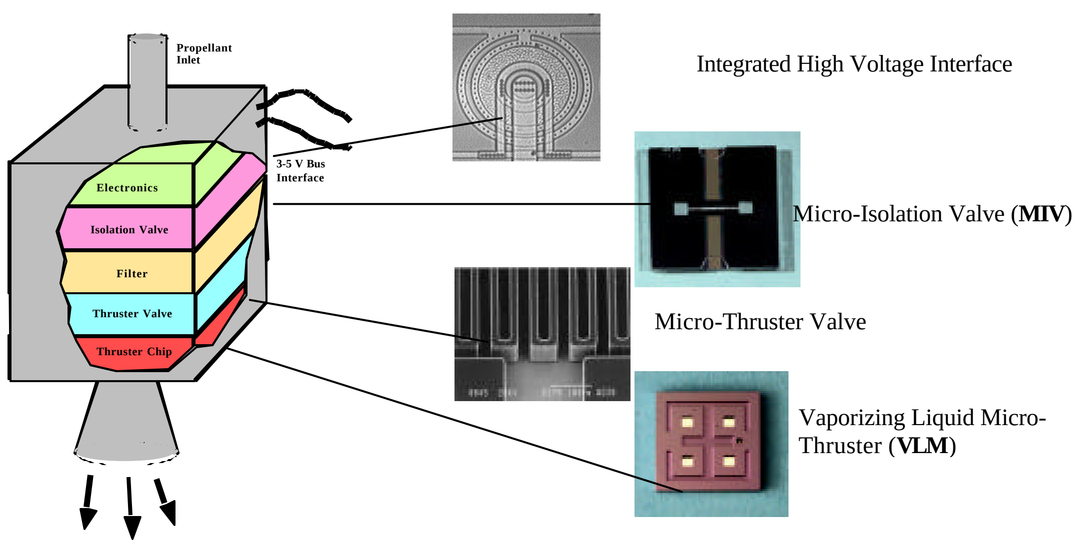


Figure 4.1-8. Complete integrated microthruster system. The ability to package disparate technologies (here with power electronics, mixed signal electronics, MEMS and microfluidics) is a key enabler in the creation of microsystems.

Advances in silicon-based imaging technologies, such as the active pixel sensor, charged coupled device (CCD), and hybrid CMOS-CCD imagers offer the promise of ultralow power and extensive integration, high quantum efficiency, and high-speed random access readout. The imagers have applications in human missions, astronomy, planetary science, and Earth science.

This technology thrust will strongly pursue the architecture studies, systems analysis, and technologies that will enable future generations of microspacecraft, microprobes, and nanorovers for both science mission applications and robotic assistants for humans on crewed missions. Miniature low-cost, highly autonomous spacecraft will allow for very frequent missions with low life-cycle costs. Fleets of microspacecraft powered by solar sails or miniature ion engines will be able to explore the solar system and beyond, as well as land on and burrow beneath the surface of any body.

Nanorovers and robots that drive, fly, hop, crawl, or burrow will provide unprecedented mobility on planetary bodies for science and exploration. Figure 4.1-9 shows a NASA designed 1-kilogram nanorover intended for surface exploration of asteroids. Groups of communicating and cooperating nanorobots or rovers will allow for large-area scientific investigations and provide "scouts" for human explorers. These microspacecraft, microprobes, and nanorobots are themselves enabled by the other technologies in the miniaturization thrust.

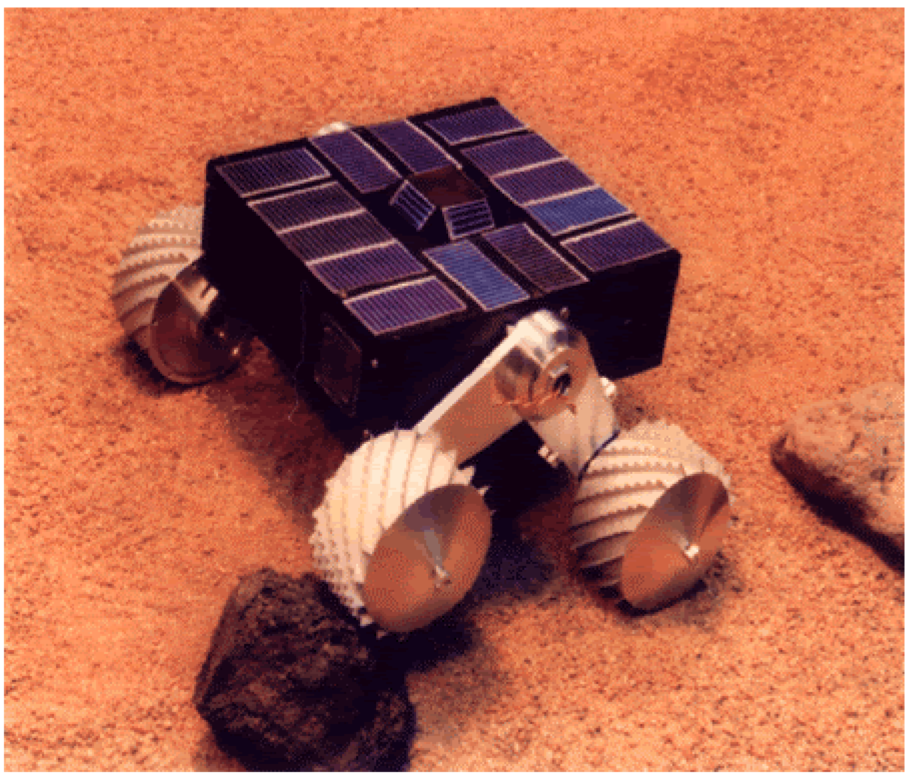


Figure 4.1-9. One-kilogram nanorover for surface exploration of planets and asteroids. Equipped with electronics able to operate at cryogenic temperatures, the rover comes with imaging, spectroscopy, and elemental analysis instruments.

Concomitant advances in a variety of nanofabrication technologies (among which are materials deposition, lithography, chemical etching, micromachining, rapid prototyping, and software design tools) will enable miniaturized chemical/biological laboratories—"labs on a chip." These are complete application-specific systems that will integrate fluid microhandling systems for extracting and reacting target molecules, microseparation technologies for enhanced sensitivity and resolution, and advanced detection technologies. Integrated microliter-scale bioassay systems are already under development for drug discovery, genetic analysis, and clinical diagnostics in the biomedical field. These miniature laboratory technologies can be tailored to address wide ranges of NASA analytical needs, including the search for specific organic molecules that could provide information on the mechanism of prebiotic evolution or possible extinct and extant life. More generally, miniature laboratory technologies can be tailored for detailed chemical and biological assessments, ranging from planetary surface and subsurface chemistry through planetary environmental monitoring and space-based clinical diagnostics, critical for long duration human space missions.

Pacing Technical Issues

The following list (table 4.1–2) provides a high-level view of important technical issues in each of the advanced miniaturization areas.

Table 4.1-2. Advanced Miniaturization Pacing Technical Issues

Micro- and Nanodevices	• Ultrafine Electron-Beam Lithography • Self - Assembled Materials and Strcutures • Wide Bandgap Semiconductors • High- and Low-Temperature Electronics • Bandgap Engineering In III-V Based (Sb, P, N) Materials • Quantum Wires and Dots • New Superconducting Materials, Devices, And Circuits • Carbon Nanotubes • Biological Materials and Structures • Physics of Nanometer, Low-Noise, and High-Power Devices • Physics of Radiation Resistance • Heteromaterial Bonding and Hermetic Sealing • Modeling and Simulation at the Nanoscale Level
Micro Machining	• Micromachining of non-silicon materials • Integration of Multiple Devices And Electronics • Actuators Capable of Macroscopic Action • Integrated Chemical/Biological Analysis Systems, Such as Sample Extraction/Preparation, Microfluidics, and Biosensors • Microthrusters, Microvalves, And Micropropulsion • Micropower Sources • Micro-Optics and Optomechanics • Space Environmental Effects • Reliability and Failure Analysis • Design Tools • Hermetic Packaging
Computation, Avionics, and Communications	• Realistic Implementations of Biological/DNA, Quantum, and Single-Electron Computation (DNA Separation Methods, 10–50 Qbit Quantum Computer, Quantum Dots, and Robust Error Correction) • Neural Processors and Genetic Algorithms • Learning Algorithms • High-Speed, Large-Format Spatial Light Modulators/Optical Processing Devices • Architectures for Novel Computational Devices • Novel High-Density Data Storage (particularly non-volatile) • Low-Power Scaleable Flight Computer Architectures • Software-Implemented Fault Tolerance • Radiation Effects on Low-Power, High-Density Electronics • Innovative Radiation Shielding • Radiation-Resistant Materials (Such As Silicon On Insulator) • Low-Power Wireless Systems (Networks And Communications to the Mother Ship) • Mixed-Mode ASIC Design and Virtual Testing in “Smart” Systems
Microsystems	• Integration of Sensors and Electronics into “Smart” Systems • New Generation Silicon Imagers, • Mixed-Signal Silicon on Insulator Technology • Micron-Scale Hybrid Bonding • Wafer-Scale Integration • Thermal and Electromagnetic Control • Architecture and Systems Analysis • Design Tools, Modeling, Simulation, and Test Packaging • Vehicle Health Management Architecture and Systems • Microspacecraft, Microprobe, and Nanorobot Architecture and Systems • Inflatable Sails and Microengines • Microprobe and Nanorover Networks and Communications • Nanomobility (Driving, Walking, Hopping, Flying, and Burrowing) • Nano “Workers” To Scoop, Dig, and Assemble

All these pacing technology issues require significant investment to secure their benefits for NASA. As a subset of these issues, the advanced miniaturization thrust endorses the findings of the NRC report, which recommends additional modest focused investments in MEMS, radiation-resistant electronics, and wideband communications, which hold promise for large future benefits for NASA.

Partnerships and Related Activities

The advanced miniaturization thrust has particularly strong interactions with the intelligent systems and compact sensors and instruments strategic technology thrusts. In some instances, the contribution from advanced miniaturization will be simply to make things small. In others, a new fundamental technique, such as quantum tunneling, is basic to advanced miniaturization. Concepts for quantum computing are principally the domain of intelligent systems, while the means to fabricate them are in the domain of advanced miniaturization. Bandgap engineering techniques leading to quantum well detectors and lasers, and superconductivity used to develop efficient high-frequency mixers are part of advanced miniaturization, but their use in science instruments is under compact sensors and instruments.

Miniaturization of NASA space systems has significant overlap with the needs and programs of other agencies and organizations. These include the U.S. Air Force, the National Reconnaissance Office, the Ballistic Missile Defense Organization (BMDO), and the Defense Advanced Research Projects Agency (DARPA). NASA has ongoing relationships with these organizations, and new partnerships will be established to ensure a coordinated and synergistic national investment in miniaturization. In addition, NASA will promote relationships with organizations such as the National Science Foundation (NSF), the National Academy of Sciences, the National Oceanic and Atmospheric Administration, and the external science community to maintain our balance of technology innovation and user pull. Furthermore, NASA as a mission agency will leverage the national investment in the technical advances made by universities. The NSF makes much of the national investment in universities, and NASA will work with the NSF to cosponsor mission-oriented research at universities.

NASA, as a partner in the National Nanotechnology Initiative (NNI), will be putting significant resources into basic research and development in nano and bionano technologies. These efforts are being coordinated with the NSF and other federal agencies in the NNI. NASA has the lead responsibility in the grand challenge of developing and infusing nanotechnology into the creation of microspacecraft with orders of magnitude more performance, reliability, intelligence and longevity than could otherwise be achieved. NASA research will also tie in and support many of the other grand challenges adopted by the NNI. More information can be found at www.nano.gov.

Industry, particularly in electronics and communications, is driving many of the areas critical for the miniaturization of NASA systems. NASA will aggressively utilize these advances and form partnerships with industry to meet Agency needs. In addition, technological advances made by NASA will be transferred to industry partners for commercialization.

4.2 Intelligent Systems

Updated 2001

NASA's bold missions in space exploration and aeronautics will require advances in many areas of science and technology (fig. 4.2-1). Among the most critical of these enabling technologies are information technology and, more specifically, intelligent systems research. The information technology revolution at NASA is twofold. First, and most obvious, computer technology is enabling new missions at lower cost; second, NASA is starting to understand itself as an information technology agency.

Thrilling, fiery launches and spacecraft are critical, but increasingly ancillary to the real purpose, which is to get our computers and sensors on station so they can tell about distant worlds visited. The Mars Pathfinder mission exemplifies a publicly engaging, interactive mission of virtual presence on the Martian surface.

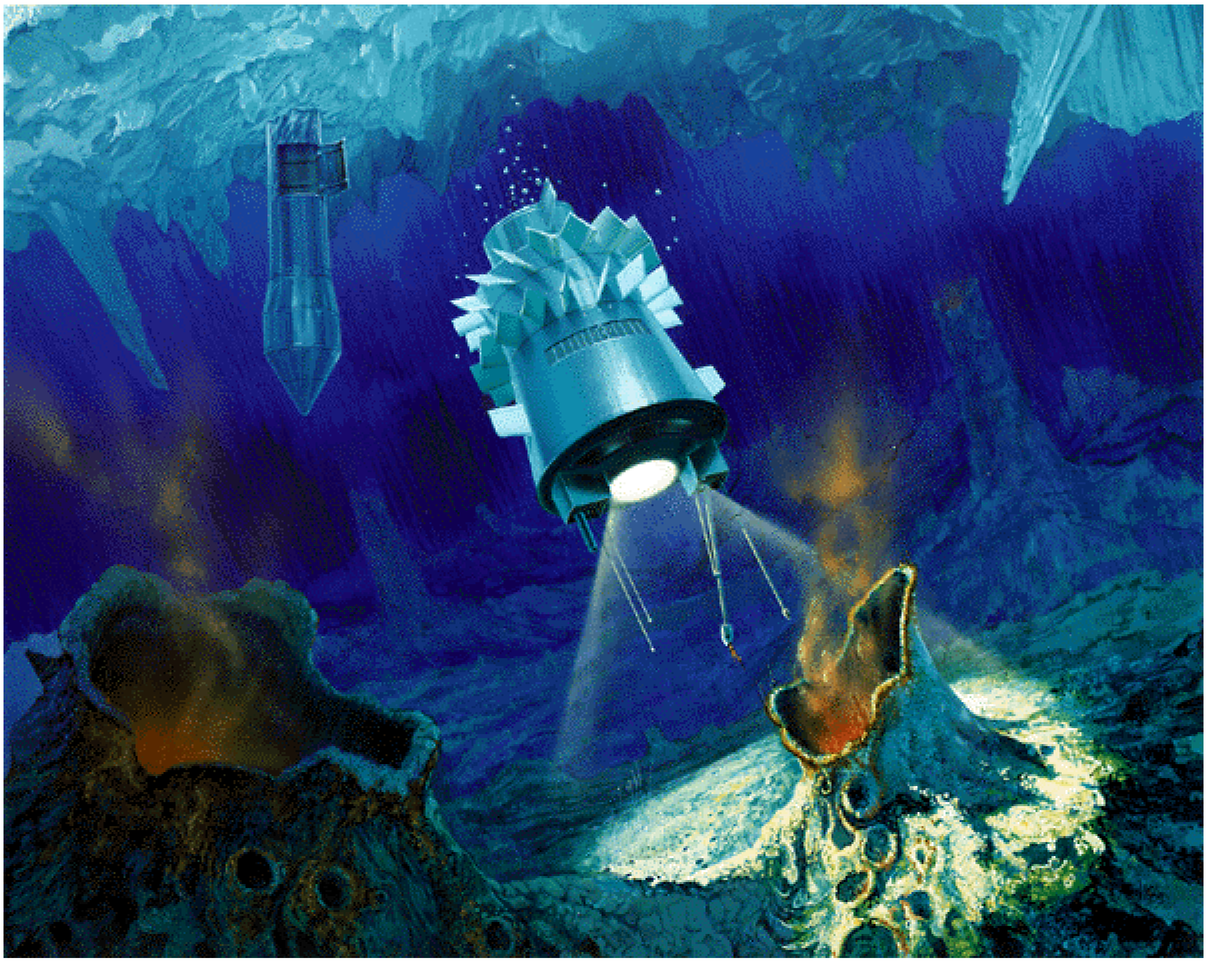


Figure 4.2-1. Underwater Europa mission concept.

Objectives

The pervasive nature of and our increased dependency on information technology, coupled with the leveraging nature of intelligent systems, will enable a wide range of applications and missions, some of which we can glimpse only dimly today, while others seem obvious. In table 4.2-1, we have identified five mission-critical application areas that must be transformed through the application of intelligent systems. We will take each critical application area and discuss how anticipated results of intelligent systems research will be the cornerstones enabling new missions at lower cost, while helping NASA meet its aeronautics “stretch” goals.

Table 4.2-1. Mission-Critical Application Areas

Mission-critical application areas	**Research cornerstones**
Autonomous spacecraft and rovers	Automated reasoning
Science data understanding	Intelligent systems for data understanding
Aviation operations	Human-centered computing
Intelligent synthesis environment	Revolutionary computing
Human exploration of space	

Autonomous Spacecraft and Rovers

NASA’s mission of deep space exploration, coupled with Administrator Daniel S. Goldin’s challenge to do it faster, better, and cheaper, has provided a requirement for one of the most exciting challenges facing the computer science research community—that of designing, building, and operating progressively more capable autonomous spacecraft, rovers, planes, and perhaps even submarines. When one considers the distances involved in deep space missions and the attendant communication delays, the value of autonomy becomes clear.

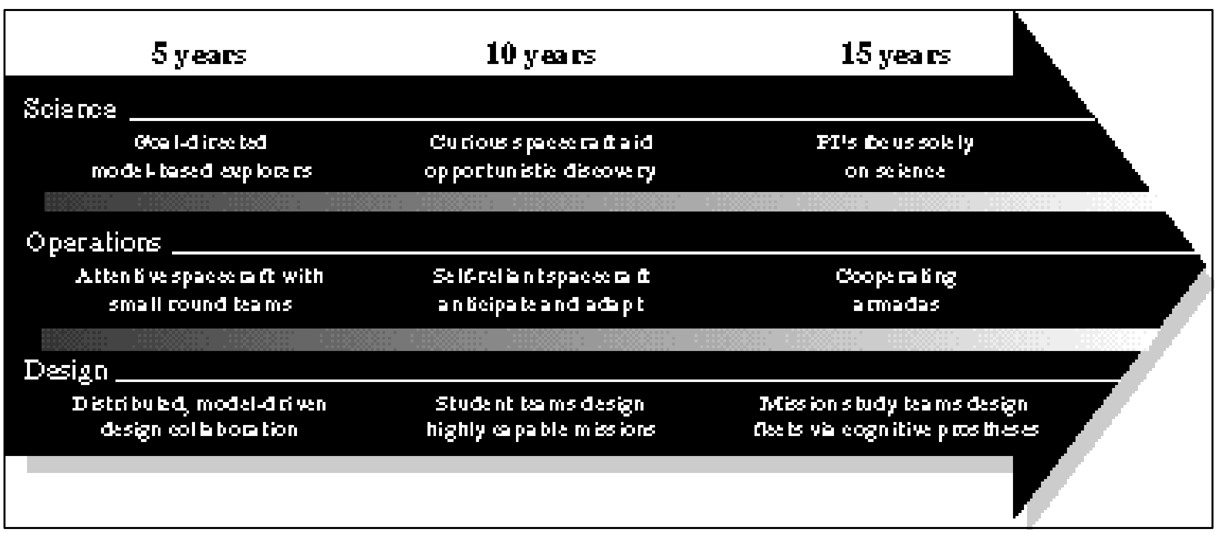


Figure 4.2-2. Roadmap for spacecraft autonomy.

NASA plans to fill space with robotic explorers, carrying our intelligence and our curiosity to explore the universe in ways never before possible. This robotic exploration of space is already well underway. Our new surrogate explorers need to be smart, adaptable, curious, wary, and self-reliant in harsh and unpredictable environments. The roadmap for spacecraft autonomy is given in figure 4.2-2.

Planetary rovers, another type of robotic explorer, also require autonomy. Uncertainty about hazardous terrain and the great distances from Earth will require rovers to navigate and maneuver autonomously over a wide variety of surfaces and independently perform science tasks. Rovers will need to become progressively smarter and more independent as their roles expand to include surveying and evaluating potential science sites, recognizing science opportunities, gathering samples, and perhaps conducting some onboard analysis.

In addition to autonomy for commanding and self-diagnosis, there is an increasing need for autonomous or semiautonomous onboard science capability (fig. 4.2-3). Deep space probes and rovers send data back to Earth at a very slow rate, limiting ability of the space science community to fully exploit the presence of our machines on distant planets. Thus, a requirement exists for research aimed at developing a new framework for autonomously performing data evaluation and observation planning aboard spacecraft. The spacecraft should be designed and programmed to gather only that information human beings consider interesting. They must not send back every bit of information.

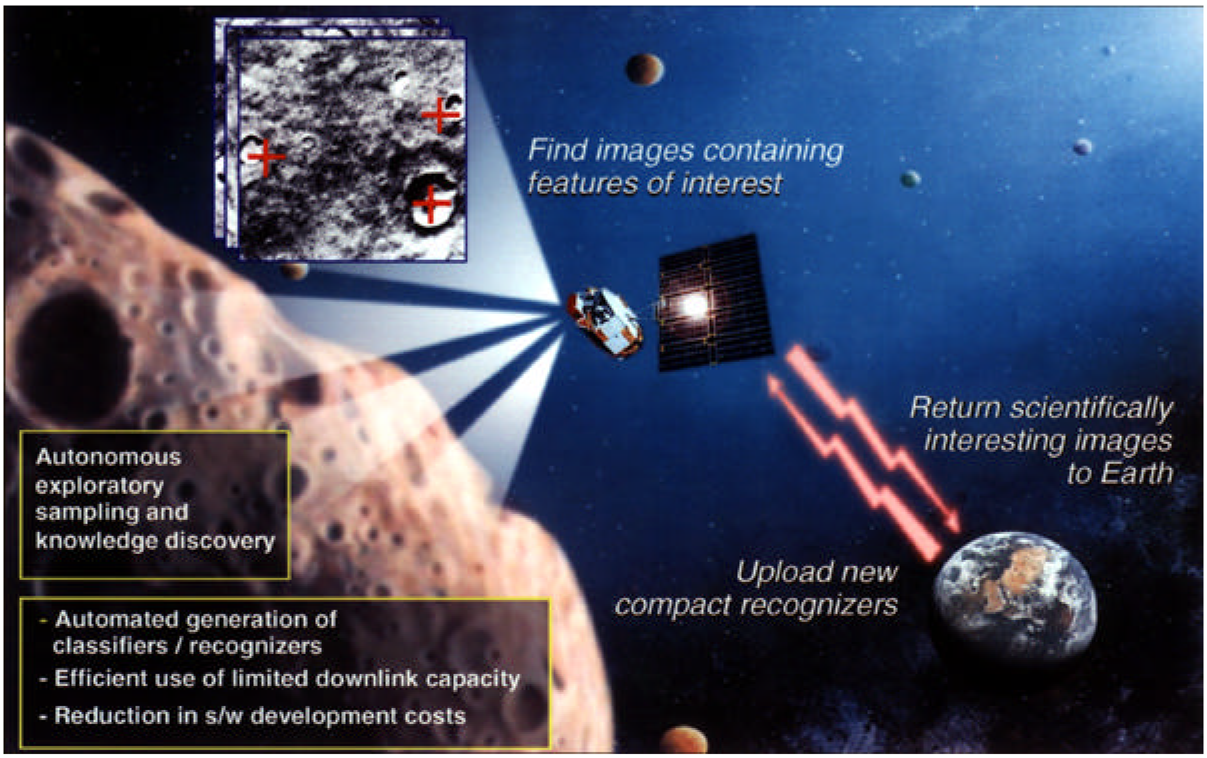


Figure 4.2-3. Autonomous technologies for onboard science processing.

Our limited communications bandwidth would be used in an extremely efficient fashion, and “alerts” from various, far-flung platforms would be anticipated with great interest by the science community. New onboard science capabilities will enable mission activities to be directed by scientists without assistance of a ground sequencing team, increasing return of quality science products while accommodating the twin realities of limited communications links and reduced operating budgets.

Relevant research areas for autonomous spacecraft and rovers include, among others, fast deduction, planning and scheduling systems, search engines, model-based monitoring, diagnosis and recovery, pattern recognition, data summarization and data mining, modeling and simulation, software development tools, end-to-end architectures, automated code generation, and advanced integration and test tools. Research on automated reasoning for autonomous systems will enable a new generation of spacecraft to perform more exploration at much lower cost than for traditional approaches.

Science Data Understanding

NASA is responsible for launching and gathering data from progressively more sophisticated orbital and deep space instruments. For example, the Earth Observing System (EOS) is being deployed to monitor global climate change. When fully operational, these sensor-rich satellites will generate about one terabyte of data per day. In addition to the obvious need for progress in high-capacity data storage and dissemination schemes, development of tools aimed at facilitating human understanding of these immense data sets is equally important. In this area, intelligent systems research can have a great impact on the ability of scientists to more fully understand and exploit the unprecedented amounts of data that NASA is now collecting. In particular, research will be needed in the areas of statistical methods for image enhancement and analysis, machine learning, and automated knowledge discovery and data mining methods.

Aviation Operations

On Earth, many of these same intelligent systems technologies will provide the catalyst for revolutionary improvements in the nation's air traffic management systems. If nothing is done, projected growth in air traffic over the coming decade will strain our already congested air traffic and ground management systems, producing an unacceptable number of accidents. President Clinton announced a major initiative to increase the safety and capacity of the aviation transportation system. NASA, in collaboration with the Federal Aviation Administration, has developed an advanced information technology system that will play a major role in realizing the twin goals of safer aircraft operation and higher throughput of airport and ground control infrastructure (fig. 4.2-4).

Figure 4.2-4. Future flight central airport traffic simulator.

Applications of intelligent systems research could include automated planning and scheduling for airport ground operations, dynamically reconfigurable aircraft, automated landing procedures, autonomous fault isolation and repair, and a new generation of performance support systems to assist pilots and air traffic controllers alike. However, as aviation systems become increasingly capable of independent initiative, how crew and autonomous systems will interact in these mixed-initiative systems is of central importance. This realization leads to the clear requirement for increased research in what has become known as human-centered computing.

Intelligent Synthesis Environment

Clearly, future missions of NASA, such as Mars exploration and many of the Aeronautics "stretch goals," involve uniquely difficult design and engineering challenges. To address these challenges, NASA will invest in an intelligent synthesis environment strategic technology to exploit advances in intelligent systems research in general, and human-centered computing in particular. The Intelligent Synthesis Environment strategic technology program is described in section 4.5.

Human Exploration of Space

As humans contemplate journeys to Mars and beyond, NASA will clearly need to exploit a wide range of intelligent systems that operate autonomously or semiautonomously in support of mission requirements. Some obvious application areas include diagnosis, automated planning and scheduling, condition-based maintenance, and performance support systems for astronauts and ground operations personnel.

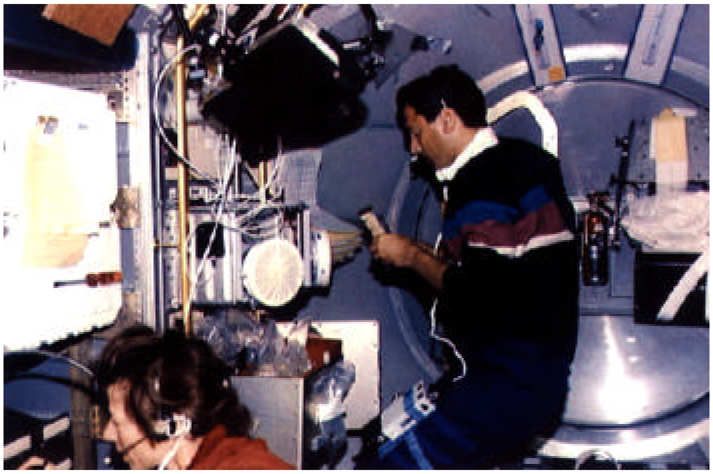


Figure 4.2-5. Astronauts working in space.

A critical requirement for NASA is to reduce the cost of operating in space. Fortunately, we anticipate that advanced information technology research will lead to dramatic reductions in launch and operational costs of space flight systems. In particular, research on human-centered computing is focused on developing powerful performance support tools to extend and leverage the capacities of ground controllers, which should radically lower operational costs by reducing staffing requirements. The problem domain of planning, integration and checkout of launch vehicles can, for example, involve the management of 4,500 tasks and 60,000 constraints. Errors or inefficiencies that delay the launch can occur, adding millions of dollars to operational costs. Increasing efficiency on the ground can, conversely, reduce the cost of access to space for mission after mission.

Likewise, intelligent systems research will greatly extend the capacities of astronauts while reducing those risks inherent to space exploration (fig. 4.2-5). As an example, consider the Personal Satellite Assistant (PSA) now in its research phase. The PSA is a softball-sized crew performance support device designed to move and operate autonomously in the microgravity environment of space-based vehicles, such as the Space Shuttle, the International Space Station (ISS), and any future exploration spacecraft. The PSA will provide the following crew support capabilities: environmental monitoring, crew work site support, communications, and remote operations support. Such innovative applications are possible in the near future; they are composed entirely of commercial off-the-shelf and Government off-the-shelf hardware controlled by sophisticated intelligent systems software.

Technical Approach

During the past two years, various groups have conducted several efforts to ascertain NASA's future intelligent systems requirements. These groups include a multi-Center team of NASA information technology researchers who produced a report called *Thinking Spacecraft*. These individuals are involved in the Autonomy and Information Management planning process and serve on various advisory committees (including top academic and industrial advisors) of the NASA Challenge of Excellence for Information Technology, which recently produced a multi-Center document titled *Information Technology at NASA: Accepting the Challenge of Excellence*. As a result of these efforts, we have converged on four research cornerstones on which NASA can build its intelligent systems future:

- automated reasoning
- intelligent systems for data understanding
- human-centered computing
- revolutionary computing

Automated Reasoning

To accomplish NASA's ambitious exploration goals, researchers must develop autonomous systems that can be commanded by simple, high-level, goal-directed behaviors, such as "make an attitude determination, followed by a course correction" or "find the next most interesting rock close by and move to it." These robotic explorers will be programmable through compositional, common sense models of hardware and operations behavior. This goal-directed, model-based programming paradigm will allow spacecraft control systems to be plugged together like building blocks from libraries of existing models, and it will permit novel behaviors to be programmed in a simple intuitive manner. Using these models onboard, automation will close the loop on sensor information at the goal level by using advanced deductive planning and execution, scheduling, diagnosis, and recovery capabilities to ensure that goals are being met. This programming paradigm has already demonstrated its usefulness in the Remote Agent Autonomy Architecture (RAAA) demonstrated on the Deep Space I mission. NASA technologists will continue to develop and exploit the RAAA aggressively for application to future missions.

Achieving capable intelligent robotic explorers will require bold new research efforts designed to borrow from nature's secrets and emulate biological solutions to sensory perception, adaptation, and motor control. Intelligent autonomous systems will need to learn from their interactions with a given environment and adapt appropriately in real time. By coupling biologically inspired neurotechnology with model-based reasoning, hybrid systems are envisioned that will use symbolic deductive methods to help coordinate and direct a collection of these adaptive methods.

As mentioned in the Autonomous Spacecraft and Rovers section, our autonomous spacecraft will need to take initiative and adapt to its environment based on curiosity and wariness. Curiosity can be understood as the ability to take action to gain information, and it draws on such research disciplines as planning information acts, decision and information theory, decision theoretic planning, model-based reasoning, machine learning, and statistics. Wariness involves the ability to assess risk, to plan contingencies and prepare backup resources, or to redirect plans to reduce risk. Research disciplines that need to develop this capability add to the list of contingent planning, reasoning under uncertainty, Markov decision processes, and Bayesian inference. Wariness also requires an ability to anticipate and adapt to subtle cues that indicate deviations from the nominal path.

While exploring the universe, these automatons often will not act alone. For example, spacecraft carrying optical units will fly together in formation to create a single deep space interferometer of unprecedented size, or a swarm of microrovers might spread out to explore a patch of Mars. Achieving this level of teamwork requires distributed coordination and collaboration capabilities. Developing this capability will require advances in distributed artificial intelligence, including distributed diagnosis, resource management and execution, coordination of heterogeneous reasoning methods, and novel coordination mechanisms taken from diverse disciplines, such as organizational theory, operations research, and economics.

Intelligent Systems for Data Understanding

Technology for onboard science data processing, along with advances in telecommunications technology, can address the challenge of limited communications bandwidth, which may worsen if NASA's vision of flying more space platforms at once is realized. With onboard decision-making, scientist-trained recognizers, and judicious use of knowledge discovery methods, a portion of the scientist's awareness can be projected to the space platform to provide the basis for scientist-directed downlink prioritization and processing of raw instrument data into science information products. This software-based partnership between scientist and space platform can evolve during the mission as the scientist becomes increasingly comfortable with the direct relationship with the space platform, as intermediate scientific results emerge, and as scientist-directed software updates are uploaded.

In addition to the need for research that leads to increased onboard science data processing, NASA technologists must find ways to help scientists on Earth understand the growing morass of data currently being warehoused. This necessary research will include biologically motivated approaches such as neural networks and genetic algorithms, knowledge discovery and data mining (KDD) research, Bayesian methods as applied to the analysis and automatic classification of data, and statistical approaches that combine information from multiple images of planetary surfaces to form a surface model at higher resolution than any particular image. Because these emerging data-understanding methods have application to data originating from both deep space and Earth-orbiting spacecraft, NASA information technology research is better enabling scientists to understand our world as well as distant worlds (fig. 4.2-6).

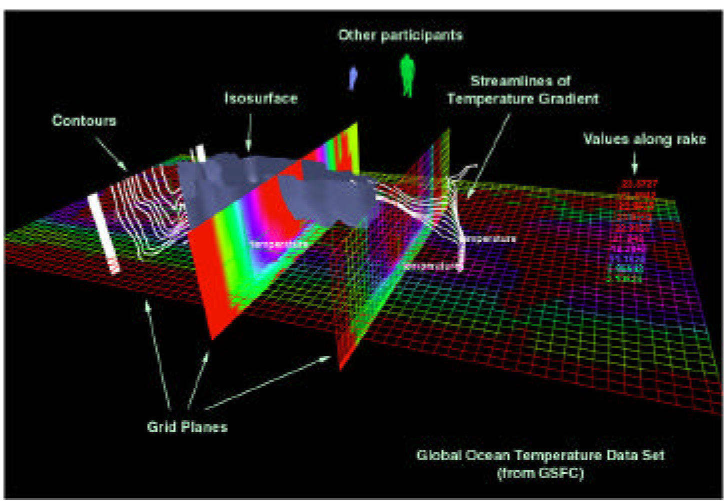


Figure 4.2-6. Virtual wind tunnel collaborative environment with ocean model example.

Human-Centered Computing

The emerging concept of human-centered computing represents a significant shift in thinking about information technology in general and about intelligent machines in particular. It embodies a systems view in which interplay between human thought and action and technological systems are understood as inextricably bound and equally important aspects of analysis, design, and evaluation. Within this framework, NASA researchers are busy inventing and deploying sophisticated computational aids designed to amplify human cognitive and perceptual capabilities. Essentially, these are cognitive prostheses—computational systems that leverage and extend human intellectual capacities, just as the steam shovel was a sort of muscular prosthesis.

The prosthesis metaphor implies the importance of designing systems that connect human and machine components in ways that synergistically exploit their respective capacities. The design and fit of these computational prostheses often require an interdisciplinary effort, which includes computer scientists, cognitive scientists, and social scientists of various types. This shift in perspective places human-machine interaction issues center to the subject. It requires a systems view whereby the system in question is not the computer, but instead includes cognitive and social systems, computational tools, and the physical facilities and environment.

Extending the prosthesis metaphor to knowledge, systems that represent scarce and exceptionally valuable information can distribute that knowledge throughout a workforce, supplement intelligence of personnel in critical positions, or give our industry partners an edge in the international marketplace. These applications range from best practice enhancements of major activities, such as managing acquisition and use of launch services, to making specialized knowledge of hazardous material handling available anywhere, anytime.

Human-centered computing may thus be defined as the discipline of integrating computer hardware and software with human performance and capabilities into a system that augments these elements toward a specified goal or objective (fig. 4.2-7). This integration is grounded in an understanding of how people and computational systems differ, suggesting what role tools can most effectively serve and how they should be designed.

Figure 4.2-7. Next generation NASA Mission Control Center.

Revolutionary Computing

Increased computing capacity is a recurring theme in the stated mission requirements across all NASA enterprises, and that implies faster processing speeds and larger memory capacities to handle a larger number of more complex tasks.

Computing requirements of NASA space missions, combined with the limitations of adapting conventional computing technology to fulfill these requirements, provides a need and opportunity to look for solutions "outside the box." Example missions in this category are those to Mars and Europa, and the use of interstellar probes. Computing models based on quantum physics, statistical physics, and biology offer revolutionary concepts that could provide true breakthroughs, increasing computing capacity in ways classical approaches cannot imagine. Advances being considered by these areas of research may allow one to address some problems currently viewed as intractable.

Quantum Computing**.** Quantum Computing, as an example of a physics-inspired approach to computing, is revolutionary in that uniquely quantum effects, such as superposition and entanglement, are exploited in the service of a new approach to computation, enabling efficient solutions to problems previously deemed intractable. Although quantum computing is in its infancy, success in this research area would have a revolutionary, direct impact on NASA's aeronautics and space exploration missions. For example, future deep space missions will be conducted largely by sophisticated, autonomous spacecraft operating in harsh environments and under extreme constraints on permitted mass, time to respond, and available electrical power. These robotic explorers will need massive computational capacity to endow them with capabilities such as on-the-fly mission replanning, real-time onboard data analyses, and autonomous diagnosis, repair, and reconfiguration, to name a few.

Biology-Inspired Approaches to Computing**.** A biological system can be viewed as composed of interacting elements that exchange and process information. In this context, these systems provide a rich source of computation models for the Automated Reasoning, Human-Centered Computing, and Intelligent Data Understanding program elements. The basic idea motivating this endeavor is learning how biological systems address the apparent complexity of autonomous activities and then exploit that knowledge to develop advanced computational systems. This approach could be particularly useful in enhancing the problem-solving capabilities of autonomous agents.

Neural computing research has led to learning and control approaches that may result in significant advances in problem solution. Much of the current work in neural computing deals with recognition of instantaneous patterns (e.g., face recognition in a static image). Biological systems, however, exist in environments rich with temporal information. The autonomous systems envisioned in this program must take advantage of this additional information.

Genetic and evolutionary algorithms use biology-inspired mechanisms of selective reproduction, mutation, and genome crossover to search for optimal structures. Genetic and evolutionary programming applies these techniques to the task of automatic programming.

Pacing Technical Issues for Intelligent Systems Research at NASA

Considering these four research cornerstones—automated reasoning, intelligent systems for data understanding, human-centered computing, and revolutionary computing—many technical issues must be resolved before intelligent systems become a reality. Pacing technical issues for intelligent systems research are listed in table 4.2-2.

Table 4.2-2. Pacing Technical Issues for Intelligent Systems Research

Automated Reasoning	• Techniques that enable the rapid development of highly autonomous systems through the specification of high-level goals and objectives • Utilizing an explicit representation of the uncertainty that exists within the world in a computationally efficient manner • The integration of knowledge-based techniques that will leverage an explicit representation of an expert's knowledge with data-driven approaches that allow adaptation over time • Tradeoffs between reactive execution and deductive inference within a real-time control loop • Anytime algorithms that allow the gradual improvement of an initial solution as additional time and computational resources become available • Integration of stochastic optimization techniques with more systematic approaches for constraint satisfaction • Advanced debugging and model-development environments to facilitate the rapid development of autonomy software by spacecraft engineers • Agent architectures that address the coordination between the varying levels of control within a distributed architecture • Techniques that enable on-board high-level science data analysis • Sensors and reflexes upon which autonomy architectures may be layered • Formal specification languages for describing both conditions that must be satisfied as well as the functionality provided by the software • Algorithms for efficiently exploring the space of possible programs • The integration of model checking and theorem proving approaches to automated verification and validation • Automated abstraction for synthesis and verification • Generating invariants from flight rules or other sources of data • Verification and validation of autonomous systems and systems that learn • Verification and validation of coupled machine/human systems, including systems for collaboration, as well as other distributed systems
Human-Centered Computing	• Innovative research on the nature, modeling, and sharing of human expertise • Research on mediating representations intended to facilitate communication and understanding • Software agent mobility, security, and behavior • Software tools for supporting synchronous and asynchronous collaboration • Engineering and mission design knowledge capture research • Tools for enabling effective distributed scientific collaboration • Knowledge organization and dissemination methods for education and outreach

	• Methods and tools for knowledge management and institutional knowledge capture/modeling • Human-centered internet tools and applications (e.g., advanced browsers) • Models and System design methods for mixed-initiative systems • Innovative human/machine interfaces and displays • Performance Support and Just-in-time Training Systems Research • Research on information overload and associated countermeasures • Tools, methods, and metrics for multi-person performance modeling • Models of cognition and collaboration capable of facilitating effective "teamwork" between humans and other intelligent agents • Methodologies for integrating cognitive task and work analysis into system design • Models for effective operator interfaces to portable and wearable computational systems
Intelligent Data Understanding	• Techniques for dealing with large or multidimensional data sets • On-line techniques for improving the predictive accuracy of a model as additional samples are collected and stored • Intelligent "polishing" of the data to handle imperfections as opposed to simple filtering • Techniques for dealing with highly skewed data that is non-representative of the solution space • Active exploration and experimentation when collecting data to ensure adequate coverage • Automated techniques for extracting new features that provide better predictive power • Techniques for finding patterns using data from heterogeneous data sources • Novel methods of inductive or nonmonotonic inference that are both rationally defensible and correspond to human inferential procedures • Methods for assessing statistical significance and adjusting the test statistic as a function of the search (e.g. randomize testing) • Specialized algorithms or biased sampling for discovering novel patterns • Generalizing intelligently from statistical data and represented knowledge • Methods that incorporate significant user input in an integrated fashion • Inductive inference making use of background knowledge • Methods for inferring causation from associations and background knowledge • Nonmonotonic or fallibilistic inference • Comprehensive theories of causality and how they apply to the analysis of data

	• Discovery of classification rules in domains (such as Earth Science) where the variables have complex interactions • Development of methods that exploit background or commonsense knowledge and combine this formalized background knowledge with data to yield approximate probabilities • Learning causal relations that can be used to evaluate alternative actions when attempting to achieve a desired outcome • Expanding, implementing and testing algorithms for using causal knowledge to predict the effects of actions • How to incorporate conjectures by human experts about the effects of the various potential actions the decision maker might make • Measuring the relevance and interestingness of a new sample • Segmentation of time-series data to detect discrete changes • Handling non-representative data sets such as maintenance records for the shuttle containing limited failure information • Integrating data-driven decision routines into a knowledge-based intelligent assistant • Unsupervised, reinforcement learning techniques that can learn a classification using delayed reward • Algorithms, which learn effectively, even from biased samples of data • Methods for supporting the inference of causation from association • Theories of causality and how they apply to the analysis of data • Active exploration and experimentation when collecting data to ensure adequate coverage
Revolutionary Computing	• Develop novel and efficient quantum and other physics based algorithms that address NASA relevant problems • Explore and expand the scope of problems that are known to be efficiently solvable using physics based models • Devise and study networks of quantum gates that can solve interesting problems • Study, develop, and assess methods to improve the reliability of a quantum computer that operates under realistic NASA conditions (e.g., noisy, Rad-hard, low power) • Conduct computational complexity research in the context of quantum computation • New computer languages capable of producing automatically the massively parallel problem solutions that could run on quantum computers • Develop useful computational simulations of proposed models • Examine physical realization and robustness by modeling and simulation • Identify and characterize potential applications of quantum computers that would strategically enable future NASA missions • Characterize the extent proposed concepts, potentially speeding up the

	solution of NP-complete problems • Develop methodologies for automating the discovery of novel algorithms from a description of physics • Understand how organisms organize the complexity of their environments • Examine biologically-inspired approaches to sensor fusion and action selection • Neural computing techniques for adaptation of control systems • Formalize strategies for organizing problems to maximize the effectiveness of evolutionary search strategies • Extract algorithms from existing biochemical knowledge of the storage, processing, retrieval, of genetic information • Enhance fault tolerance based on immune systems • Explore biologically-inspired computational substrates such as DNA computation and neural circuitry • Understand and exploit how recurrent neural networks recognize and act upon temporal patterns in data • Construct systems capable of carrying out biologically-inspired computation at very large scales

Other Activities That May Contribute

In today's era of constrained budgets, it is particularly important that, wherever possible, NASA be a smart, demanding customer of information technology. We should collaborate with industry, academia, and other Government agencies to the greatest extent possible. If we reinvent many wheels or try to build them all ourselves, NASA will not be able to afford much space exploration. With that said, there are problems that Silicon Valley is not going to solve for us, and in those areas we must endeavor to perform and support some of the world's best research.

The Department of Defense is sponsoring significant relevant research in several areas, specifically software agents, haptic interfaces, next-generation Internet-based tools for performance support and just-in-time training, biologically motivated computing, and other areas. NASA is well positioned to leverage this work effectively. In addition, the NSF sponsors a wide range of basic intelligent systems research potentially relevant to NASA. For example, NASA's human-centered computing effort is well coordinated with the NSF and with the Defense Department's extensive efforts in this area through a cross-agency working group (represented by 10 agencies) that meets monthly.

4.3 Compact Sensors and Instruments

Updated 2001

Compact sensors and instruments comprise a strategic technology that is fundamentally important to the success of NASA's Space Science and Earth Science Enterprises, and that plays a crucial supporting role in both the Human Exploration and Development of Space and the Aerospace Technology Enterprises. Mission success of the two science enterprises directly depends on the availability of remote sensing and in situ sensing systems that enable new and/or improved measurements of scientific parameters from a variety of surface, airborne and spaceborne platforms, and that reduce the cost of those missions. Without continued improvements and innovations in this area, progress in space and Earth science will be severely restricted. Improvements in human exploration of space, space development, aeronautics, and space transportation also directly depend on systems that accurately measure a wide variety of hardware performance and environmental characterization parameters.

As NASA ventures into an era of increasingly challenging missions, the next generation of sensors and instruments must be innovative in scientific and technological capabilities, while conserving limited resources such as mass, power, volume, and end-to-end cost. Systems that use minimal resources are generically designated "compact;" however, the term does not exclude systems that inherently require large resource allocations. In these cases, compact refers to the decrease, typically by an order of magnitude or more, of the required resources in comparison to state-of-the-art systems.

Objectives

Generating a new set of compact sensors and instruments based on the development and infusion of cutting-edge technology will enable significant increases in mission performance and capabilities while reducing the costs of scientific measurements. Developing compact sensors and instruments has always been a NASA goal, but this objective was often compromised to meet stringent performance requirements that could not yet be achieved with miniaturized approaches. In the future, compactness will be necessary to achieve affordable missions and to drive the development of instrument architectures and technologies that enable classes of missions previously unattainable.

Each NASA Enterprise has articulated its science research plans and associated capability needs, as captured in Enterprise Strategic Plans and other technology planning documents, and as summarized in section 3 of this document. This section highlights the technical objectives in the area of compact sensors and instruments that are expected to offer the greatest benefit to NASA in achieving these ambitious plans at an affordable cost. Although specific applications for future sensor systems vary across the NASA Enterprises, the desired advances can be summarized in the following categories:

- remote receivers/detector systems
- compact instrument architectures
- active sensor systems
- local sensors
- integrated payloads
- distributed sensor systems

Technical Approach

To meet these objectives, the new generation of compact sensors and instruments will depend on innovative systems engineering and the development of key technologies. Six broad technology classes have been identified above as candidates for significant advances and are therefore likely to have a major impact on development of the next generation of compact sensors. Each class is discussed below in terms of recent developments and possible areas of enhancement. These are to be considered as examples of research and development tasks. They do not constitute a complete list.

Remote Receivers/Detector Systems

Driven primarily by military surveillance needs, the development of high-sensitivity, large-format CCD arrays initiated a great leap forward in high-resolution imaging that benefits both space and Earth science applications. Recent advances in "smart sensor" arrays that incorporate active electronics at the pixel level offer flexibility and simplicity in readout architectures. Further advances are desired to achieve higher levels of on-focal-plane integration to incorporate more sophisticated signal processing and micro-optics for beam focusing and filtering. Many measurements also call for larger full-well capacity per pixel. Advanced array architectures produce instrument capability enhancements in terms of image pixel count, dynamic range, measurement speed, instrument size, flexibility and simplicity of operation, operation in extreme temperature and pressure environments, and insensitivity to background radiation. In some cases, they enable types of measurements that were simply not practical with previous technologies.

The extension of detector array technologies into other wavelength ranges translates directly into a concomitant extension of imaging and spectrometry instruments. For example, the Department of Defense investment in HgCdTe and InSb technologies has led to the availability of moderate-to-large-format arrays that cover the near and thermal (mid) infrared (IR) regions. Further development for lower readout noise, lower dark noise, lower power, larger formats, and higher radiation tolerance is required. IR arrays that do not require active cooling are also desirable for reducing the power and size of future instruments. The far IR region, replete with scientifically valuable species-specific molecular and atomic transitions, has not been comparably developed. Quantum-well infrared photodetector technology has the potential for extending low-cost, large-format arrays through the thermal IR into the far IR. Further development of arrays in the highly sensitive silicon impurity-band conduction technology is also desired. On a longer time scale, band-gap-engineered materials, and nanostructures such as quantum dots discussed previously in the Advanced Miniaturization section, offer wavelength tailorable high sensitivity across the far IR. To achieve the highest sensitivities in the IR requires that both the optics and focal planes be cooled to cryogenic temperatures. Long-life, low-vibration, high-efficiency coolers are therefore required for temperatures down to a few degrees K.

Array technology for ultraviolet (UV) light also needs improvement. Long-term solutions include arrays based on visible-blind wide-band-gap semiconductors such as the nitrides and diamond. In addition, improved microchannel plates for fast timing, zero read noise, and visible-blind applications may be fabricated using lithographic manufacturing techniques.

High-energy astrophysics missions would greatly benefit from arrays with improved performance. Development in materials and fabrication processes could enable a new generation of devices with deeper depletion depths to extend the response to higher energies and with an increased resistance to radiation damage. In other devices, changes in gate structure would enable the band-pass to be extended toward lower energies. For several of the high-resolution X-ray spectrometer technologies, such as cryogenic calorimeters, there is a need to develop construction and readout schemes that will allow for the production of large-format arrays. At higher energies, arrays based on materials such as CdZnTe should allow for the development of imaging gamma-ray spectrometers that would be significantly more compact than those using older technologies requiring low operating temperatures.

The application of some detector technologies developed for high-energy experiments at the large particle accelerators could enable a new class of cosmic ray measurements. Advanced two-sided Si strip detectors, scintillating optical fibers, and solid-state replacements for photomultipliers, along with accompanying application specific integrated circuits (ASICs) to read and preprocess the outputs, could greatly advance the field. New technologies extending arrays of energy-resolving pixels from the high-energy regime to a longer wavelength also offer considerable size reduction while enhancing performance by eliminating the need for separate lossy spectrometer components in the optical path.

Coherent IR, submillimeter-wave, and millimeter-wave radiometers and spectrometers provide the high sensitivity, high spectral resolution and the parallel processing required for rapid detection and identification of scientifically important chemical species in terrestrial and planetary atmospheres and in astrophysical sources. Heterodyne spectroscopy also provides critical information on the dynamics, kinetics, and energy balance of the sources being studied (e.g., planetary atmospheres, the interstellar medium, comets, etc.). Miniature low-mass, low-power heterodyne receivers in these wavelength ranges (10 ? m to about 1 mm) must be developed. Important areas of development include local oscillators, mixers, compact optics, and array architectures.

The extension of millimeter-wave MMIC technology to 700 GHz is desired to simplify the spectrometer design, with an emphasis on power reduction and wide spectral bandwidth (fig. 4.3-1). Low-power spectrometers with more than 100 channels and millimeter-wave array mixers with ~ 50 elements are needed to provide mapping capability for future atmospheric limb-sounding missions. Ultra-compact systems are also needed for planetary orbiters or landers that have much more constrained mass and power budgets.

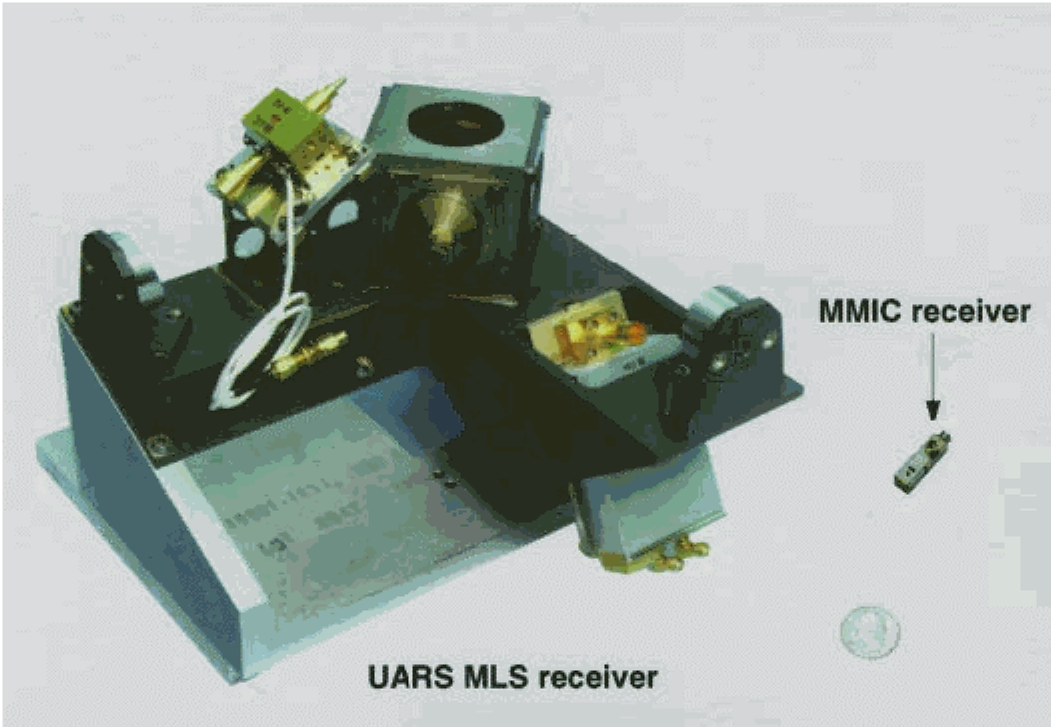


Figure 4.3-1. Downsized Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) receiver using MMIC technology.

A broader range of scientifically important chemical species for astrophysics and atmospheric science can be detected and studied by extending the frequency of heterodyne instruments into the THz regime. One of the greatest challenges at these frequencies for heterodyne radiometers is generating the required 1 to 10 mW of local oscillator power needed to pump single-element room-temperature semiconductor downconverters or multiple-element superconducting arrays. Today's technology relies on high-order multiplication of sources near 100 GHz, a very inefficient and limited-bandwidth approach. Breakthroughs may come from a variety of different approaches including direct oscillator technology such as the nanoklystron, higher-frequency amplifier development, such as 500 GHz HBT devices, photonic sources such as photomixers and photoconductors, and harmonic mixing for pumping at higher multiples of the local oscillator reference frequency. New downconverter technologies are also very promising and can close great gaps in the THz spectrum.

Reducing this power requirement with new types of mixer elements is also possible. High-speed metal-semiconductor-metal (MSM) photodetectors are being pursued to address this need. Superconducting bolometer mixers with photo-mixer local oscillator sources implemented in both low critical temperature (Tc) and high-Tc materials represent another promising approach. Compact, efficient coolers are also required, cooling to 60 K for high-Tc and to 2 K for low-Tc systems. Mixers based on two-dimensional electron gas (2-DEG) quantum-well devices and the new MgB_2 superconductor are also promising, and have the advantage of requiring cooling capabilities intermediate between those of low-Tc and high-Tc systems.

Heterodyne imaging arrays at mm and submillimeter wavelengths have the potential to dramatically increase the science return of observational astrophysics missions. Large-format architectures (mixer devices, planar antennas, and optics) and ultra-low-power backend microwave spectrometers with 200 to 1,000 channels must be developed to meet this need.

Infrared systems enable the study of important molecular species at a higher spatial resolution and probe additional pressure regions. The goals of infrared heterodyne spectrometer development consist of semiconductor laser and miniature gas waveguide laser local oscillators stable to 100 kHz, and broadband (>3 GHz) mixers extending capabilities into wavelength regions longward of 12 ? m, and developing array spectrometers. Approaches include developing semiconductor and quantum well technologies for lasers, and interdigitated electrode resonant optical cavity and quantum-well approaches for mixers and mixer arrays. Novel bandgap engineering approaches including quantum cascade devices and superlattice structures offer opportunities to extend laser wavelengths farther into the IR. Unique optical designs, including holographic and diffractive optics, need to be developed for the generation and combination of arrays of signal and local oscillator beams.

The next generation broadband measurements of the Earth's radiation budget will require detectors that are spectrally flat from 0.6 to 100 ? m, with an order of magnitude increase in sensitivity. High temperature superconductor bolometers currently offer a fourfold improvement in sensitivity and are the best candidates for achieving the 10-fold improvement in sensitivity at the required wavelengths. Developments in thermopile and thermistor bolometer technology may also enable some advances.

Compact Instrument Architectures

The size and power requirements of remote sensing instruments can be reduced through innovative architectural approaches. Comprehensive measurements of atmospheric chemistry (gases, temperature, and moisture) can be achieved with wedged-filter imaging spectrometers or Fourier Transform Spectrometers operating from the visible through the far IR region. Novel Fourier Transform Spectrometer designs need to be developed to enable an order of magnitude reduction in spacecraft resources while preserving the quality of the science return. One advance is the development of smooth diamond membrane beam splitters that can cover 1 to 1,000 microns in wavelength, thus permitting a much smaller system. Other spectrometer approaches should be examined, including electronically tunable filter spectrometers and hyperspectral systems. Electronically tunable spectrometers need to be extended through the thermal IR region. Hyperspectral imaging, where system spectral resolution is matched to narrow-band spectral features to be discriminated, can be improved using innovative grating and prism optical systems.

The emerging technologies of lithographically defined and holographic optics enable the automated manufacture of significantly more complex optical elements, and the concomitant simplification of the physical optical system. Lithographic optics can also improve the performance of optical systems by reducing system aberrations. On-chip electronically tunable filters can eliminate both the bulk and wear vulnerability of moving parts inherent in mechanically scanned optical systems.

Many space and Earth science applications require large collection apertures to detect very weak signals, to achieve high spatial resolution, and/or to perform other collection or shielding functions. Examples include deep space imaging, microwave imaging of soil moisture, outer planet solar energy collection and communications, and sun shields for missions flying close to the Sun. A number of innovative approaches are being pursued to achieve large-area collection/imaging optics in the operational configuration while maintaining low mass and short linear dimensions during launch (fig. 4.3-2). These approaches include segmented optical surfaces, inflatables, deployables, broad-band diffractive lenses, and sparse (unfilled) aperture architectures. For high-resolution imaging, surface conformation must be held to within a fraction of the wavelength of the light being detected, resulting in very demanding precision surfaces and element control for imaging at optical and near-optical wavelengths. Approaches involving deformable micro-optics replicated over large areas are also being explored.

There is also a need for miniature low-mass, low-power, high reliability scanning and actuator systems for remote-sensing instrumentation. These systems may use all solid-state, current, or field activated polymer or ferroelectric materials. This technology will enable new remote sensing instrument configurations consistent with a sensorcraft paradigm. The use of appropriate composite materials in instrument mechanical structures, components, and optics can permit lighter and stronger systems with better thermal and mechanical properties.

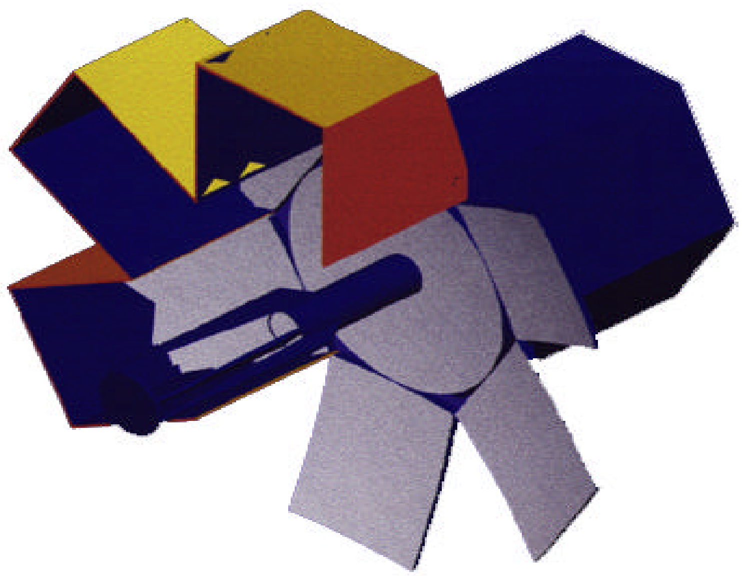


Figure 4.3-2. Lightweight, deployable telescope reduces mass and launch volume.

Active Sensor Systems

Spaceborne lidar offers a powerful new tool for profiling physical and chemical properties of atmospheres as well as for measuring topographic and gravitational properties. Reliable, efficient laser transmitter sources are required for Earth and planetary remote sensing science missions (fig. 4.3-3).

Two classes of laser transmitter are targeted for near term (0 to 5 years) development. The first class is either tunable or fixed frequency, with output energies from 0.1 to 1.0 J at 10 to 100 Hz, 3- to 50-ns pulses, 0.02- to 100-pm stability, and wall plug efficiencies greater than five percent. These laser systems must produce outputs in the wavelength region from the UV to the mid IR. The second class of lidar systems, currently being addressed with fiber lasers, requires miniature laser transmitters with greater than 20-percent wall plug efficiency, 0.1- to 100-? J energy/pulse, 1- to 10-pm wavelength stability, 1- to 10-ns pulse widths, 1 Watt average power, and 1- to 5-kHz pulse repetition rates. High-speed, low-noise photomultiplier tubes and avalanche photodiodes in the visible and near IR and signal processing electronics are being developed for return signal detection.

Active microwave instruments are also important remote-sensing tools; however, they are particularly energy demanding. Low-power, low-mass options for sources and electronics are sought. Significant advances in efficiency and sensitivity are required to allow the power of radar sensing to be exploited in missions beyond near-Earth orbit. Thin-film antenna electronics for implementation on deployable structures are also important. In the future, better signal extraction will be obtained through multiple-beam antennas, and more sophisticated synthetic beam patterning will be possible with advanced electronic beam steering.

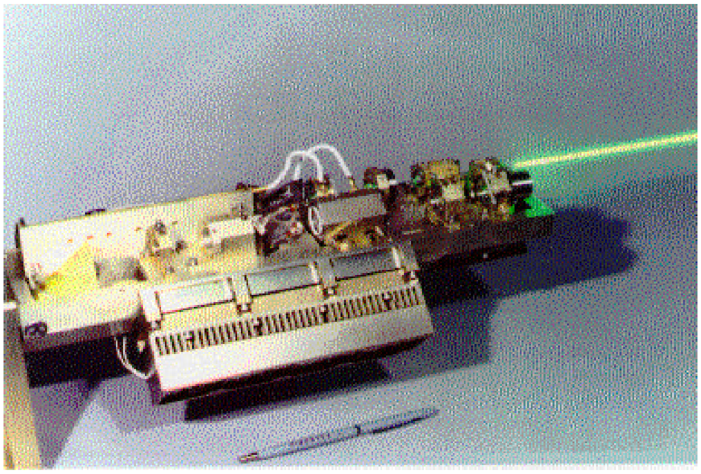


Figure 4.3-3. Solid-state laser transmitter.

Local Sensors

Missions that orbit Earth or other bodies in the solar system—or merely survey objects as they fly by—rely on detection at a distance, which limits measurement modalities to the sensing of electromagnetic radiation or extended fields. Future missions that come in direct contact with the body or its atmosphere can take advantage of a much broader range of in situ biogeochemical measurements. The primary constraints on in situ instruments are mass and power, requiring extreme miniaturization. NASA is developing miniaturized analytical tools for a variety of in situ elemental, chemical, biological and mineralogical analyses. Robotic sample acquisition and preparation also present significant challenges, and innovative measurement approaches requiring minimal sample manipulation are a priority. For example, the recent development of an atmospheric electron X-ray spectrometer incorporates an electron-permeating membrane that obviates the need for the sample to be placed in vacuum for the analysis.

In situ measurements also allow optical techniques not feasible in remote sensing. Local optical sources can be used for in situ absorption, luminescence or scattering measurements of atmospheric, surface and subsurface chemistry, and other parameters such as local wind speed or the water content of planetary minerals. Raman scattering, typically too weak to detect at a distance, is potentially a powerful technique for in situ biochemical analysis. Rugged, narrow-band, tunable diode lasers are a necessary component for many of these local optical techniques. A microlidar system incorporating a code-modulated transmitter laser of 100 to 200 mW can be used to extend wind and opacity profiles up through the entire atmospheric boundary layer.

For biochemical assays, extensive sample preparation is typically unavoidable.
Standard analytical techniques often rely on a room full of glassware dedicated to sample manipulation and preparation. Since biochemical analysis is critical for both the in situ search for life and the maintenance of astronaut health on long-duration missions, NASA is developing integrated biochemical analysis packages. A "lab-on-a-chip" would combine sample acquisition, manipulation and preparation, signal processing, power management, and wireless communication with micro or nanoscale sensors. Microfluidic platforms incorporating flow channels, pumps, and valves also offer the advantage of working with samples on the nanoliter or subnanoliter scale, such that reagent usage is minimized.

Human presence in space also requires a suite of environmental monitoring sensors to ensure safe air, water, and food for astronaut consumption. Sensors targeting specific compounds are useful for a set of priority chemicals such as oxygen or carbon dioxide levels in the air, or the presence of fuel contamination in the cabin. Approaches capable of detecting and discriminating a broad range of possible contaminants are also being developed. Examples include a miniaturized mass spectrometer and sensors mimicking the biological nose and tongue functions. An electronic nose contains an array of sensors with varying responses to the presence of a wide range of chemicals, such that response patterns across the array become the signatures of specific chemicals or chemical combinations. NASA is currently supporting the development of an electronic nose based on resistivity changes in polymers seeded with conducting particles (fig. 4.3-4).

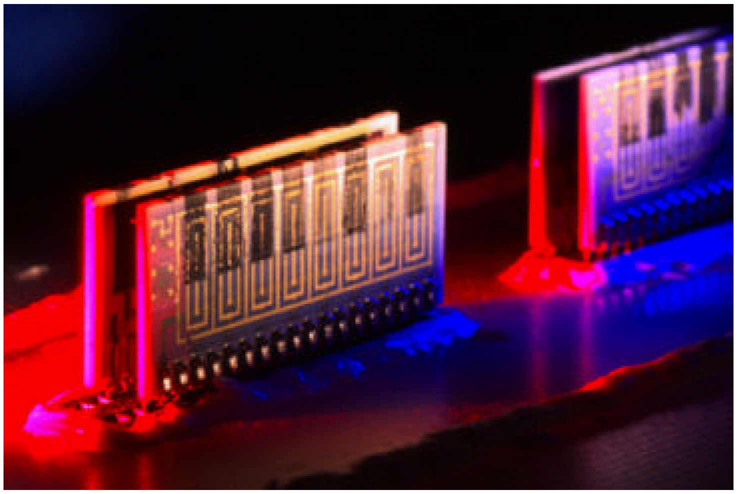


Figure 4.3-4. Electronic nose based on an array of conducting polymers.

Integrated Payloads

Highly capable microelectronics and microspacecraft systems, by virtue of their broad applicability and potential for reducing mission costs and development times, enable missions that would otherwise be prohibitively expensive. However, without concomitant reductions in size and mass of payload instruments, and their ability to be integrated into these systems, the science return of these missions would be limited. Emerging chip-level sensor technologies offer the realization of this paradigm. Many of these opportunities are based on MEMS technology, discussed in section 4.1. Sensors of interest include fields and particles instruments, chemical and biological sensors, linear acceleration and rotational motion sensors, and meteorological sensors; in general, any point measurement that does not require a large collection aperture for sensitivity may be a candidate for MEMS miniaturization. With the emergence of nano-scale sensors and the nano-scale equivalent of MEMS technology (NEMS), additional orders of magnitude in system miniaturization will become possible.

Architectures encompassing multiple functions in a single system are also being explored. For example, a single optical system can be designed to serve multimission functions, including science imaging, navigation imaging, optical communications, and/or solar power collection. The extension of this multiplexing approach to chip-level systems and the strategy for moving toward fully integrated microspacecraft are discussed in more detail in section 4.1.

Distributed Sensors Systems

Some types of science investigations are enabled only through suites of correlated measurements. For example, predictive weather and climate models require a set of correlated meteorological data from a grid of points spaced on a scale matched to the distances over which these parameters vary. Similarly, an array of seismometers enables not only the location of the origin of a seismic event; it can also provide information on the transmission of seismic waves through the interior, thereby generating a three-dimensional map of the Earth or another planet. When a large number of interrelated measurements are required, a sensor web capable of self-determination of node locations and interconnections offers a powerful new measurement approach. Early examples of limited sensor webs are currently being realized, but approaches for scaling such systems in analogy to the human nervous system still require development.

Interferometry is another measurement technique based on distributed sensors. An interferometer senses the phase difference of light from a single source arriving at two separated points in space in order to determine the position of the source with great accuracy. Since the angular resolution of an interferometer depends on the separation of the collection points, space-based interferometry using multiple spacecraft at immense separation opens a new window on high-resolution imaging of distant objects. In essence, the suite of spacecraft comprises the instrument, and its operation relies on exquisite control of the constellation geometry. For future interferometry missions to perform as desired, the relative positions of the spacecraft must be maintained within a centimeter, and the spacing between the surfaces of optical elements of the distributed optical system must be controlled to the picometer level. High-efficiency laser sources, such as may be possible with vertical-cavity, surface-emitting lasers (VCSELS), are also a necessary development for laser-based control metrology. Coolers operating down to 50 mK are required for IR interferometry.

Pacing Technical Issues

Progress in developing the technologies discussed previously is typically governed by one or more pacing technical issues. These are technical problems that must be resolved for the items to be used fully in the development of compact sensors and instruments. Some examples of the desired technologies and their current technical issues are listed in table 4.3-1.

Other Activities

In many cases the driving needs for the Department of Defense and NASA converge, and NASA can benefit from investments being made by other agencies. For example, the Defense Department investment in development of CCD technology and HgCdTe and InSb IR arrays for space-based surveillance has benefited NASA science investigations considerably. Over the past decade, BMDO has been the primary source of funding for space-based sensor development across the visible, IR, and radio frequency regimes. However, this support has been drastically curtailed in recent years, as the charter of BMDO (formerly the Strategic Defense Initiative Office) has evolved to focus on ground-based systems, and has moved beyond technology development into implementation.

At present, U.S. military forces and the National Reconnaissance Office are the primary government supporters of advanced sensors and instruments for airborne and spaceborne platforms. The Army has consistently led Defense Department efforts in enhanced night vision, and is currently supporting work on quantum-well infrared photodetectors, advanced HgCdTe materials, and integrated micro optics. The Navy is pursuing hyperspectral imaging to augment the understanding of coastal ocean characteristics. The Air Force is using this technology to detect and identify hostile targets. The National Reconnaissance Office is supporting the development of advanced space-based surveillance and reconnaissance systems. BMDO continues to support some advanced sensor system development for ground-based implementations. The Department of Energy and the Environmental Protection Agency are also involved in remote imaging and in situ chemical measurement, with the primary application of waste site hazards detection and mitigation.

Table 4.3-1. Examples of Desired Technologies

Key Technologies	Current Technical Issues
Remote Receivers/Detector Systems	Materials uniformity and process control, both of which directly impact yield Diffractive and holographic optics Cost and chip-level integration of sensor and processing electronics
Compact Instrument Architectures	New remote-sensing techniques and mechanisms (both passive and active) to maintain rigidity/shape in post-launch environments
Active Sensor Systems	High-efficiency power conversion systems
Local Sensors	Miniaturized, integrated sample acquisition and preparation systems Integration of sensors, sample manipulation, processing electronics, and signal transmission system
Integrated Payloads	Development of interchangeable standardized chip sets that combine multiple functions and are usable in space environments
Distributed Sensor Systems	Architectures and protocols for scaling to high-node-count smart sensor webs Techniques for exquisite point-to-point and surface metrology and control

Both the Air Force and the Army are supporting the development of lasers for ladar and lidar applications. The Air Force leads the work on high-power lasers and amplifiers for target and hazard detection, for motion sensing, and for profiling of atmospheric winds. The Army is developing Sb-based laser diodes for amplitude-modulated radar and technologies and systems for millimeter-wave, ultrawideband, and synthetic aperture radars. The Air Force focus is on foliage and ground-penetrating radars, phased-array systems, and bistatic radar detection systems in which existing radio frequency sources, such as radio and television broadcasters, provide the illumination.

In the microsensor systems area, the Environmental Protection Agency and the Department of Energy are pursuing small in situ packages for monitoring chemical and biological hazards; DARPA is the primary developer of integrated MEMS sensor systems. The Air Force, Army, and Navy also have small microsensor programs that emphasize unattended ground (or ocean) sensors primarily to detect enemy activity. NSF also funds fundamental work in materials, sensors, and MEMS primarily at universities.

The investment areas of other agencies should be monitored to avoid unnecessary duplication of effort. In particular, NASA should monitor the development of technologies for high spatial and spectral resolution imaging, for passive and active remote measurements in the IR and radio frequency regions, and for miniature in situ packages.

4.4. Self-Sustaining Human Support

Human exploration beyond low-Earth orbit will be a major thrust after completion of the International Space Station early in this century. In preparation, NASA is examining an array of candidate destinations that have high scientific value and which would represent a logical step forward in human exploration of our solar system. Candidate destinations include the Moon, libration points, Mars, and asteroids. These destinations can be categorized into two mission classes: 100 day or 1000 day. A mission and systems analysis was conducted on each of these candidate destinations to identify core capabilities and common technologies that are independent of the specific destination option chosen. These capabilities and common technologies, along with long lead-time low TRL destination unique technologies, provide the basis for an exploration technology development strategy. The technologies described in this section were derived from this study. Extended on-site human exploration and development of extraterrestrial space will lead to revealing, exciting, and unpredictable scientific discoveries, a burgeoning expansion in human knowledge, and enrichment of the human experience. Before long-duration human exploration missions to the Moon, Mars, and other solar system destinations can be planned, however, technologies must be developed that will enable self-sustaining operations in hostile environments far from any effective support from Earth. This section describes three groups of long-term technologies that will lay the foundation to eventually enable affordable, safe, and productive extended human operations beyond Earth orbit. (See table 4.4-1.)

Table 4.4-1. Three Groups of Technologies That Will Lead to Self-Sustaining Human Support

Human support technology areas	**Technology elements**
Human health and performance	Health and space medicine Radiation protection Human factors and crew systems/supplies
In situ resource utilization	
Advanced systems and operations	Advance life support Extravehicular activity and surface mobility Habitats Telerobotics (telepresence) Surface power Advanced operations

Human Health and Performance

Health and Space Medicine

Human health and performance in space may be affected by a number of factors, including the effects of zero-gravity and reduced-gravity deconditioning, radiation exposure, and the effects of unexpected illnesses or accidents requiring medical treatment (fig. 4.4-1). The effects of extended exposure to zero gravity and reduced gravity is a major NASA research activity that is based on previous Russian and American space program experiences. This activity will be significantly extended, with experience to be gained on the ISS. Technology must be developed to provide effective countermeasures to the deconditioning effects of zero gravity and reduced gravity. The space radiation hazard to human health must be understood through multidisciplinary research into the physics, biology, and risks involved in various levels of radiation exposure. Providing adequate radiation protection for human beings engaged in deep space and planetary surface exploration activities requires that materials technologies and innovative designs for spacecraft, habitats, and suits must be investigated. Medical technologies must be developed to enable essentially autonomous capabilities for the exploration crew to diagnose and treat a wide variety of potential illnesses or traumas. Examples include expert diagnostic systems, noninvasive examination and monitoring, compact and lightweight medical equipment, and extended life pharmaceuticals and blood substitutes.

Figure 4.4–1. In-space health examination.

Radiation Protection

The potential hazard and impact of radiation on human activities in space has been recognized for four decades. Recently, with mission duration increasing and mission planning beyond Earth orbit, the assessment of risks to humans from space radiation and the mitigation of those risks have become imperatives, with risk decisions playing a major role in future spacecraft design, mission planning, and even crew selection. Advanced spacecraft and mission design, including cost and schedule, will be driven by the decisions made regarding what is acceptable radiation risk. Quantitative assessment of risk depends upon sufficient knowledge in five major areas.

1. Environment Definition — The three primary radiation sources in space (trapped belt radiation, solar particle events, and galactic cosmic rays) are dynamic and vary temporally, spatially, and in particle energy distribution. Environment models are constructed by using

empirical data. With the exception of the galactic cosmic ray model, the quality and accuracy of current models is poor. Dynamic models of the environments are not available. Predicting (forecasting) solar particle events (onset, size, duration) with sufficient accuracy for operational decisions is not currently available.

2. Shielding and Materials — Adequate shielding of the incident space radiation is an effective strategy in mitigating radiation exposure. Current radiation transport codes do not sufficiently describe particle interactions within the shield material and the emerging particle distributions (species, intensity, and energy distribution) that exit the shield. Shielding materials include new materials (composites). Current shielding models are limited to simplistic geometries.

3. Radiation Effects on Humans — Data describing the effects of exposure of humans to ionizing radiation is limited to atomic bomb survivors. Little, if any, data exist regarding exposures of humans to space-type radiation species. The effects of exposures to the heavy ion component of galactic cosmic ray radiation are poorly understood. These data are critical to permit adequate assessment of radiation risk.

4. Radiation Monitoring Strategies — Efforts to predict or forecast solar particle events (onset, rise time, event size, spectral rigidity, and duration) have been unsuccessful. Some large solar particle events are not produced by solar flares but by coronal mass ejections. The largest variations in solar particle event peak fluxes seem to be associated with interplanetary shock. Instrumentation systems (and resulting model development) are required. In addition, active instrumentation is needed to provide real-time assessment of the radiation environment and resulting crew exposures.

5. Countermeasures — Radiation exposure countermeasures include spacecraft design, mission planning and operations, shielding, and pharmacological systems and protocols. Specific goals of the radiation protection technology development are to (1) define all aspects of the radiation environment to within ± 20 percent; (2) improve radiation transport codes and shielding geometries by a factor of two; (3) quantitatively assess the risk of radiation exposure of humans to space radiation, understand the effects of such exposures, and reduce the uncertainty of the risk assessment to a factor of three; (4) improve solar particle event forecasting to the level of predicting Earth weather; and (5) develop pragmatic shield designs and effective pharmacological countermeasures within 10 years.

Pacing technical issues include an accurate risk assessment of human beings' exposure to space radiation, an understanding of the uncertainties of the estimate, and the mitigation of that risk. Dynamic environment models and solar particle event forecasting techniques are urgently needed. Countermeasure development is in its infancy. In addition, a major concern is the availability of a ground-based heavy ion accelerator for the required basic research.

Human Factors and Crew Systems/Supplies

Human factors and crew systems/supplies cover a broad spectrum, including human-machine interfaces; ergonomics; crew productivity; habitability, food preservation and preparation; the recycling of crew systems materials such as plastics, clothes washing/drying, and repair/maintenance systems; and a host of other items. The difference between using current technologies and developing inexpensive, low-risk, new technologies for crew systems/supplies can be responsible for a 25- to 50-percent reduction in overall mission mass and cost because reductions in crew systems/supplies act as a 10-to-1 mass lever in reducing vehicle and fuel mass, as well as development cost.

Human factors and crew systems also seek to provide a safe, efficient living and working environment for the crew and—backed by expert systems, robust electronic knowledge bases, and detailed system models—to permit crew-autonomous operations so that a small, Earth-isolated crew can take on the roles now performed by multitudes of ground-based experts. To reduce mass, many of the human-machine interfaces will be moved into a synthetic computer environment in the spacecraft, viewed with head mounted displays, and actuated via tracking systems and cyber gloves. Other new technologies must also be developed to enable human exploration missions. Currently, we have no ability to store a complete diet for the 2 to 3 years required by Mars missions. Shelf-life extension, with completely new preservation technologies, will determine whether a Mars mission is even possible. Technologies for "from-scratch" cooking and the processing of crops or other raw materials into edible foods have yet to be developed.

Furthermore, the complexity of vehicles required for long-duration missions, the high probability of equipment failure, communication times up to 20 minutes each way, and the impossibility of resupply all make an adequate intravehicular maintenance system a critical and enabling component for these missions. Many new technologies and advances will be needed to reduce the mass of such a system while guaranteeing that it can respond to contingencies, including lightweight, multipurpose tools, spare parts, hoses, wire, connectors, supplies, methods for mocking up integrated circuits, decision and expert systems, troubleshooting information storage (drawings, procedures), and so forth. Methods for in-flight training must also be developed to maintain the sharp skills that may have originally been learned years before their use and to meet the unexpected, and untrained for, needs of the crew.

Pacing technical issues include

- Body-worn interfaces that generate a deep symbiosis between man and machine, including virtual interfaces, embedded real-time intelligence with decision support and context-driven data retrieval, and natural language interfaces.
- System design information capture to allow the experience of ground-based engineers and experts to be included in a near-autonomous, Earth-isolated environment.
- Nonintrusive methods for monitoring individual and group performance over time to identify, warn, and correct for human performance deficits caused by the unique stresses in exploration-class missions.
- Methods for preserving a complete diet for 3 to 5 years to enable a Mars mission.
- Technologies for reducing, reusing, and recycling crew systems/supplies to produce massive reductions in mission mass/cost for future exploration missions.

Work is underway in the area of human-machine interfaces in the academic, military, and commercial communities. Also, commercial and military applications of augmented reality/virtual interfaces, embedded real-time intelligence and decision support, and natural language interfaces are being studied.

In Situ Resource Utilization

The great explorers of the Earth learned to live off the land as they ventured far from their own support bases. Likewise, it is fundamental to any program of extended human presence and operation on other solar system bodies that we learn how to use indigenous resources. The research objectives of this area are to understand the availability and possibilities of those resources and to develop the mechanical, chemical, and biological processes and supporting technologies that will enable us to use them to support human life and operations. The chief benefits of in situ resource utilization (ISRU) are reducing both the cost and the risk of human exploration by decreasing Earth launch mass and by increasing crew access to caches of consumables.

A key subset of ISRU, which, in particular, has significant cost and risk reduction benefits for robotic and human exploration, and which requires a minimum of infrastructure, is in situ consumable production (ISCP). ISCP involves manufacturing and storing rocket propellants for surface ascent and Earth return, life-support gases and water for crew and fuel cell reagents for power generation and storage. For example, systems analyses of human Mars missions have indicated that producing propellants on the surface of Mars by processing atmospheric carbon dioxide can reduce the initial mission mass required in low-Earth orbit by approximately 20 percent as compared to carrying all required return propellant to the Mars surface from Earth. An even greater leverage can occur for lunar and Mars missions when in situ water can be processed.

ISCP facilities can be divided into three interconnected subsystems: (1) resource collection and conditioning, (2) chemical processing, and (3) product liquefaction and storage. ISCP concepts for the lunar exploration primarily consider the use of regolith (soil containing metal oxides) and ice, which recent evidence indicates exists at the lunar poles. For Mars exploration, the primary feedstock initially under consideration is the atmosphere (95 percent carbon dioxide, 3 percent nitrogen, 1 percent argon), which is used to produce oxygen. Manufacturing fuels on Mars, such as methane, methanol, or other hydrocarbons, will require either Earth-supplied hydrogen or access to indigenous water resources.

Though not critical for initial human exploration, eventually sustained long-term human presence on the Moon, Mars, or other solar system bodies will require the ability to construct human base facilities by using local materials. Important enabling technologies will be those associated with the extraction of local materials and their conversion to plaster, fibers, plastics, glass, ceramics, and metals useful in manufacturing and construction.

Pacing technical issues include

- Resource Collection and Conditioning — ISRU depends on realistically available resources. Technologies for resource collection and processing on the Moon include autonomous shoveling, grinding, sorting, sifting, and separation of lunar regolith. For Martian atmospheric resources, advanced adsorption pumps and/or mechanical compressors are required. Lunar resource collection technologies may also be applicable for Mars soil and water extraction processing.
- Chemical Processing — Chemical and energy efficiencies can significantly affect power requirements and Earth-supplied consumable needs. Chemical reactor technology challenges include oxygen extraction from lunar metal-nonmetal oxides, high-efficiency chemical-fuel

production reactors, water and carbon dioxide electrolysis units, recirculation and boost pumps, and efficient water and gas separators.

- Product Liquefaction and Storage — The benefit of using ISCP depends on the cryogenic system performance. Minimizing the mass and power associated with product liquefaction and cryogenic storage, while maximizing system reliability, will be a challenge. Key areas for technology advancement include oxygen liquefaction, long-term cryogenic storage, and autonomous cryogenic fluid transfer hardware. Furthermore, because the ISCP propellants will be stored in the ascent vehicle propulsion system tanks, cryogenic storage performance will also affect ascent vehicle and propulsion system designs.
- Survivability — ISCP plants will be operated in incredibly harsh environments without maintenance, so components must be both robust and long-lived. ISCP hardware will need to demonstrate lifetime capabilities not currently found in terrestrial chemical production plants. Also, because many ISCP processes operate at high temperatures with regular, diurnal cycling, the development and selection of new materials will be important.
- Autonomous Operation — If ISCP facilities are predeployed to a planetary surface, human crews will not be available to control the operations directly. Communication time delays, particularly for Mars and asteroid operations, require facilities to operate autonomously with built-in failure detection and recovery capabilities— a major concern, even for terrestrial petrochemical plant operations. Technology challenges include highly reliable sensors, advanced simulation and modeling software, and development of flexible control and failure detection, isolation, and recovery software.

Related work is underway in the Departments of Defense and Energy. Millions of dollars have been spent on developing technology for these programs that can be leveraged.

Advanced Systems and Operations

Extremely reliable, long life, robust, self-diagnosing, self-reconfiguring, and self-maintaining systems are the visionary goal for the systems that will support long-duration human operations in deep space. Technologies must be developed that enable lightweight, extremely reliable regenerative life support capability (i.e., systems that regenerate air and water and other consumables by processing and reconstituting waste products). Robotic assistants and mobility aids must be developed to make human operations safe and to make their scientific investigations productive. Intelligent expert systems will be needed to assist the crew when the base is attended and to manage operations with minimal remote assistance from Earth during periods in which the on-site crew is absent.

Advanced Life Support

It is imperative that life support systems operate with increased autonomy and minimize consumables, for considerations of both safety and cost and to ensure crew health. Using advanced life support technologies provides this autonomy and increases productivity of the mission by reducing mass, power, and volume necessary for human support, thus permitting larger payloads for science and exploration. Two basic classes of life support systems must be developed—those directed toward applications on a transportation/habitation vehicle and those directed toward applications on the planetary surfaces; in general, those systems compatible with microgravity and those compatible with hypogravity environments. The technical objectives of advanced life support are as follows:

- Provide technologies that significantly reduce life-cycle costs, improve operational performance, promote self-sufficiency, and minimize the expenditure of resources for missions of long duration; specific goals should
  - fully close air and water loops to eliminate expendables.
  - develop and integrate resource recycling/processing and contaminant control systems to increase self-sufficiency.
  - optimize food loop closure, with concomitant air and water revitalization, based on the growth of crop plants.
  - provide efficient, reliable active thermal control (heat acquisition, transport, and rejection).
  - develop fully regenerative integrated systems technologies that provide air, water, food, and resource recovery from waste.
- Resolve issues of microgravity and hypogravity (reduced gravity) performance through space flight research and evaluation; specific goals are to
  - develop predictive models of fluid and fluid/gas behavior and interactions in reduced gravity that can be used as a basis for design of new hardware.
  - achieve equivalent productivity, control, and predictability of bioregenerative life support components in microgravity (as on Earth) and characterize performance of bioregenerative systems at Lunar and Martian gravities.
  - demonstrate reduced gravity performance of gravity-sensitive life support hardware components and subsystems.

The pacing life support technical issues are to improve biological water processing effectiveness in microgravity, to recover resources from solid wastes, to process food from plants grown on site, to preserve food long-term (more than 3 years), and to minimize power and thermal rejection requirements for plant growth (from approximately 100 kW per person to about 20 kW per person).

Related work is underway in many other Government and industry programs that address water recovery, crop breeding, control and monitoring, and automation.

Extra Vehicular Activity and Mobility

Extended human operations on the ISS will require a significant amount of extravehicular activity (EVA) tasks during the assembly and operational phase of the project. The experience gained during these extensive EVA's will contribute greatly to the design changes that will occur in more advanced EVA systems that will be used during future long-duration missions beyond low-Earth orbit. More comfortable, lighter weight suits will be the new design goal. The goal is to greatly increase the mobility of the EVA suits and increase the EVA sortie capability from 8 hr to 12 hr, while simultaneously reducing the mass of the suit by one-third. These refinements will be added without risking the primary purpose of the EVA system, which is to sustain an astronaut's life in the harsh environment outside a spacecraft.

The impact of zero-gravity deconditioning on the crew's ability to conduct subsequent surface operations and development of approaches in dealing with these effects is a significant concern. For example, the typical transit time for an Earth-to-Mars mission is 150 to 200 days. Because this extended time in zero gravity will contribute to bone and muscle loss in the crew members, these astronauts cannot be expected to walk great distances easily when they reach Mars. There is a plan to develop robotic technologies that will assist EVA crew members in their traverses across the Martian surface. These technologies range from small, autonomous tool caddies to large, pressurized four-wheeled rovers, with the capacity to provide life support for up to four crew members and a range of hundreds of kilometers beyond the main landing site.

Pacing technical issues for this area include a regenerable carbon dioxide removal system that does not require the use of any consumables, a suit cooling system that does not use water as a consumable, and a portable life support system (breathing system) for Mars that uses in-situ-produced cryogenic oxygen.

In a related external activity, several proprietary industry concepts for carbon dioxide removal systems are currently under development.

Habitats

Space and planetary surface habitats are pressure vessels that provide the living quarters and support systems needed by human crews engaged in space exploration. Structural and materials research and technology development is required for the very lightweight and comfortable habitats needed for the months of transport to distant destinations and for the months, and possibly years, which human beings will spend on the surface of the Moon or Mars performing exploration activities. Such habitat technology is also important because it has the potential to open up the possibilities for near-Earth-orbital platforms for commercial use. Major technology interests are in advanced lightweight materials, the use of inflatable design techniques, and techniques for providing protection from micrometeroids, orbital debris, and radiation protection. Related activities are underway in several other Government agencies.

Telerobotics (Telepresence)

Telerobotics technologies have proven to be tremendous magnifiers of human space exploration efforts to date and are expected to play an even more essential role in future missions. The use of remote manipulator arms on the Space Shuttle, the planned use of similar arms and the additional functionality of dexterous manipulators in the assembly and maintenance of the ISS, the recent demonstration of a free-flying inspection robot from the Shuttle, and the spectacular successes of the telepresence operated Sojourner robotic rover, which landed on Mars in July 1997, are all harbingers of the role that robotics and telerobotics will play in support of future human space exploration. In addition to the application of telerobotics to orbital and interplanetary spacecraft, many of the surface systems required for human missions to the Moon and Mars will be telerobotically deployed, checked out, and operated for months or years before the human crews arrive. Crews on the surface of the Moon and Mars will telerobotically control remote rovers and remote sampling equipment. Crew robotic assistants will assist in the operation and maintenance of the surface base systems and in surface exploration activities.

Goals for telerobotics technology include developing and demonstrating improved remote sensing, inspection, and manipulation that will lead to increasing the operational capability, safety, cost-effectiveness, and the probability of success of NASA missions. Quantitatively, this telerobotic capability would enable a minimum of 50 percent of the required extravehicular work needed in orbit and on planetary surfaces by the year 2004 to be performed by telerobotic means. The functions provided include on-orbit inspection, assembly and construction, processing, servicing, and repair. Planetary surface applications include exploration, construction, site preparation for human presence, processing, servicing, and repair.

A specific near-term goal has been set to produce a lightweight (< 1 kg), low-cost (less than $500,000), highly autonomous EVA robotic camera that can operationally roam and station-keep about interplanetary vehicles or platforms located at libration points at a separation distance of 1 in. to 1 mile. A second midterm goal is the development of a space robot EVA associate/surrogate with human-in-a-suit perception and dexterity performance with 50 percent life-cycle cost of the current ISS baseline. A longer term vision is the development of technologies that will enable affordable, coordinated robots that can deploy, assemble, and construct laboratories, habitats, and facilities at libration points, on asteroids, and on planetary surfaces.

Pacing technical issues for telerobotics include increasingly reliable and higher performance in-space and planetary surface mobility, perception, and dexterity (with greater navigational accuracy between the robot and the workspace), while reducing flight system weight, and operational cost. Related work in terrestrial robotics is underway in the Departments of Energy and Defense. Canada, Japan, Europe, and Russia are also supporting related activities.

Power Systems

Advanced power systems are required for interplanetary vehicles, platforms at libration points, human base operations, human surface exploration operations, drilling and mining operations, and ISRU. Power requirements may range from 20 kW for a typical lunar exploration base, to 50 kW for a typical Mars surface exploration base, and into the multi-megawatt (mW) range for propulsion systems of interplanetary spacecraft. Advanced power system technologies are critical to developing an affordable approach to supporting human life and operations while in transit to and on the surface of other solar bodies. Power systems must be very lightweight, extremely reliable, and able to operate for years without significant human maintenance. Example technologies that are being considered are advanced, highly efficient and lightweight solar photovoltaic systems; thermoelectric conversion; regenerative fuel cells for energy storage; fuels extracted from planetary resources; and nuclear reactor systems. Generally, solar technologies are mass and volume competitive at the lower power levels, while nuclear systems scale more favorably with higher power levels and in areas where continuous power is needed.

Many power system technologies are important for both robotic space exploration and human space exploration. Robotic missions can be a proving ground for the larger, more robust systems required for human beings. Also, many of these technologies are directly applicable to the commercial aerospace sector where large infrastructures of Earth-orbiting satellites will provide real-time global communication and information access. For example, recent improvements in photovoltaic cells and batteries have greatly benefited Earth orbiting commercial missions by extending satellite life times and increasing payload capability. Some specific goals for advanced power technologies are listed in table 4.4-2.

Table 4.4-2. Goals for Advanced Power Technologies

Technology	Goal
Fuel Cells	20,000-hr life Greater than 400 Whr/kg
Photovoltaics	30-percent efficiency 300 W/kg Large, deployable structures
Energy Conversion	> than 20-percent dynamic conversion > than 15-percent static conversion
Power Management	> than 2,000 V (dc/ac) distribution and control
Reactors	> than 25 W/kg (system level) – 10's of kW > than 100 W/kg (system level) – multi-mW systems

Pacing technical issues include reactor power system components, high-density/long-lived energy storage, and high-efficiency, low-mass solar arrays. Related activities are underway in the Department of Defense in solar cells, batteries, and power management. The Department of Energy is supporting efforts in high-efficiency thermal-to-electric conversion.

Advanced Operations

Self-sustained, long-duration human operations in deep space will require a new paradigm for vehicle systems and subsystems design, a culture shift in ground and onboard operational techniques, and the development of new innovative-enabling operational tools to be both cost-effective and safe. The focus will be on vehicle and ground systems technology developments that will require minimal human operational intervention when in use. Less human intervention will drive operations costs down and should improve safety. Vehicle systems technology developments that are extremely reliable and modular, offer long service life, are self-diagnosing and self-repairing, and require little to no real-time ground or onboard human attention will be sought across the crewed programs. This paradigm will be applied to resource providing systems, transportation systems, teleoperated systems, life support systems, EVA systems, and communication systems.

Operational support capabilities based on cutting-edge information systems technologies will be required to enable the reduction in real-time, around-the-clock ground support and training (operations costs) and/or to reduce flight-crew-required attention to maintenance, monitoring, training, and planning (leaving more time for science). This technology area will draw heavily on enabling tools developed in intelligent systems, the intelligent synthesis environment, and the deep space systems technology areas.

Ground-flight-control techniques must change to make long-duration, long-distance missions affordable. Minimal flight control ground support will be the target. Distributed payload/science/biomedical operations are envisioned. Control centers may be a thing of the past as connectivity-enabling technologies will allow for communication capabilities that downplay the perceived team need for physical proximity. Flight crews could provide their own flight day planning and vehicle resource management with only minimal effort. Management action teams composed of subsystem managers, flight dynamics, payload, science, biomedical, and even flight crews could form virtually. The average civilian could log on to the vehicle web site and be placed virtually in space or on a remote planet.

As new techniques, tools, and systems are developed for use in deep space crewed missions, they can be tested by using existing space assets. The Space Shuttle and the ISS are prime testing grounds for developing/testing/certifying the new and revolutionary operational techniques, tools, and systems.

Pacing technical issues include the following:

- Requirements for automated vehicle and crew health monitoring, fault detection/prediction, and action recommendations.
- Fully automated guidance, navigation, and control.
- The development of onboard planning-scheduling systems that provide ease of use and autonomous flight crew planning operations.
- Spacecraft and habitat-based training tools with embedded training instructor capabilities required for systems, science, biomedical, and flight control operations tasks.
- Robust telepresence systems.
- High-data-rate deep space communication links.
- Virtual reality force feedback systems.
- Wearable, high-speed, and low-battery-consumption computer systems.
- Space-ground network standards—interoperability.

4.5 Deep Space Systems

Updated 2001

While space offers the potential of answering fundamental scientific questions at the core of human curiosity, the space environment is also very hostile and unforgiving (see figure 4.5-1). Besides operating at extremes in terms of temperature, pressure, and radiation, there is a particular set of formidable issues associated with operations at extreme distances from Earth and, in some cases, the Sun.

These "deep space" missions challenge the basic physics of propulsion systems needed to cover astronomical distances—power systems that must function when the Sun appears no brighter than some stars, communications systems that must convey high data rates across vast distances using virtually no power, and sufficient onboard intelligence and autonomy to phone home only to deliver new insights. These ambitious, robotic, long-lived missions, designed and executed at the limit of the technically possible, extend human reach to the solar system's very center and beyond its edges.

When we look 40 or 50 years into the future, we see a time when the Origins program will have borne fruit and identified those star systems having a planet hospitable to life among the thousand stars nearest the Sun. A robotic probe to that star system will be a natural next step for the space program. Such a mission will be far from an extrapolation of today's planetary missions. An interstellar probe will require the application of physical processes we cannot today employ in such disciplines as propulsion, communications, power, computing, and autonomy. Even the pursuit of such technology advances will revolutionize planetary exploration and enable science return from interstellar precursor missions not possible today.

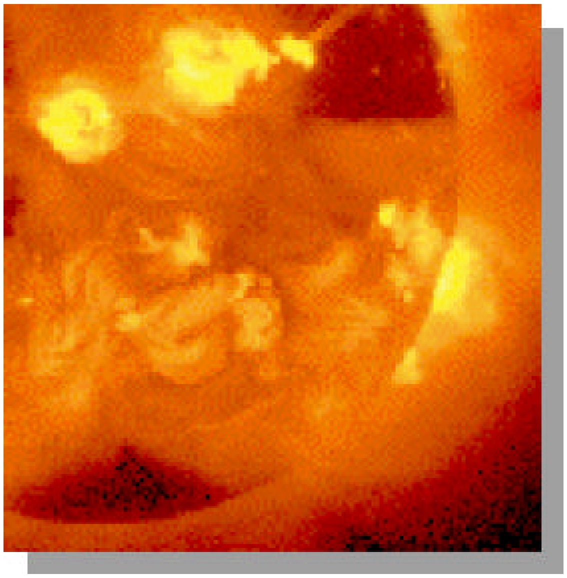


Figure 4.5-1. Hostile environments of space.

This section describes the technology necessary for deep space missions primarily managed by the Space Science Enterprise. Deep space missions provide both a technological challenge and an exciting opportunity for NASA. The challenge arises because the frequent, affordable missions contemplated by the Space Science Enterprise and delineated during the recent science planning meeting at Galveston, Texas, depend on the use of small, inexpensive launch vehicles and small, sophisticated robotic spacecraft. The technological capability to produce such spacecraft does not exist today. The opportunity surfaces because meeting this challenge will establish a technical capability to produce small, affordable spacecraft subsystems that will revolutionize the design of military and civilian Earth satellites, providing unequaled national capability.

The Deep-Space Systems Technology Plan will address principal disciplines and describe capabilities needed to allow the vision of future space science to be realized, spanning the development spectrum from research to demonstration as appropriate. Only the highest priority advances are described, and it is assumed that advances being pursued in the interest of commercial and military satellites that benefit deep space missions will be assimilated into the repertoire of capabilities available to designers of deep space missions and spacecraft. Furthermore, the implementation of the Deep-Space Systems Technology Plan will take advantage of the best capabilities to be found within NASA, academia, the Department of Defense, and industry.

Deep space systems technologies fall into the following five areas: power, propulsion, communications, autonomy, and robotics. Several additional technologies are identified that may be required for specific classes of deep space missions.

Deep Space Electric Power Technology

The electric power generation, storage, and management for deep space missions present many unique challenges and requirements. Operations in extreme temperature and high radiation environments are major mission drivers. Power generation options, in particular, heavily depend on proximity to or availability of solar energy. In addition, the need to rendezvous, enter atmospheres, descend, and land and operate on or below the surfaces of planets, moons, and small bodies results in requirements for high-impact resistance, resilience to dust or particulates and atmospheric gases, or special thermal management techniques.

Power Generation

Power generation may be accomplished by converting solar energy at distances up to and perhaps somewhat beyond two astronomical units (AU). However, at significantly greater distances, spacecraft will have to rely on the conversion of thermal energy from onboard nuclear sources for power.

The goal for solar photovoltaic is to extend the use of solar energy over the longest possible distances from the Sun and to as many landed planetary/small body sites as possible. To do this, technology developments are needed in several areas, as follows:

Lightweight solar arrays (> 100 W/kg) are essential to the use of solar photovoltaic at great distances from the Sun (> 2 AU). Such distances will require large collection areas; thus, thin-film solar cells along with ultra light deployment structures, including inflatables, will be needed to minimize launch masses.

High-efficiency solar cell technologies (> 25 percent conversion efficiency) are being rapidly developed by industry. However, high-efficiency solar cells must be developed with radiation resistance for missions near Jupiter or the Sun, with the capability of nondegraded performance under low solar intensity and low-temperature (LILT) conditions at large distances from the Sun. For surface power generation, low intensity light and low temperature conditions similar to those experienced in deep space may also be experienced in planetary regions, even near the Sun (such as in polar regions).

Special photovoltaic system technologies may also enable the wider use of solar energy. Concentrator optics may expand the use of high-efficiency solar cells to well beyond the asteroid belts at 2 AU. Also, substantial technology development is needed to provide the high-temperature components necessary for operation of solar arrays near the Sun.

The goal for thermal-to-electric conversion from radioisotope/nuclear power sources is to enable efficient use of nuclear fuel for deep space missions when the solar flux is insufficient for solar operations, including planetary surface and subsurface activities. Technology needs in this area include the following:

Static thermal-to-electric technologies, such as segmented thermoelectric, alkali metal thermoelectric conversion (AMTEC), or thermophotovoltaics, offer high efficiencies with no moving mechanical parts (fig. 4.5-2). High power density (> 10 W/kg), quiet, and long-life operation is the payoff for power sources in the range of a few hundred watts (alkali metal thermoelectric conversion and thermophotovoltaics, near 20 percent efficiency and 10 W/kg and segmented thermoelectrics, potentially up to at least 15 percent efficiency) down to milli-watt power sources using thermoelectric technologies.

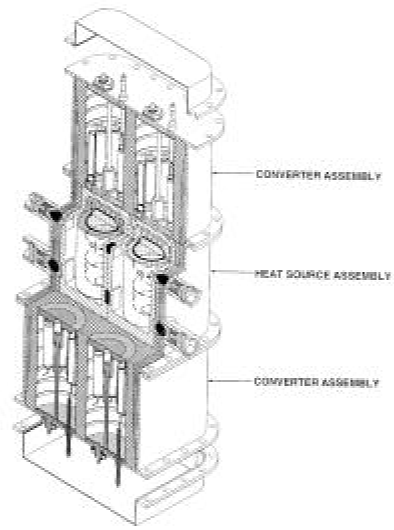


Figure 4.5-2. Conceptual diagram of AMTEC Power System.

Dynamic thermal-to-electric technologies, such as Stirling and Brayton cycle engines, may also play a role in nuclear power sources when the effects of moving parts are not a factor or can be minimized. They may be used in applications from a few watts (Stirling) to many kilowatts (Stirling and Brayton) (fig. 4.5-3). Dynamic conversion is typically considered enabling for large, reactor-based surface power systems in the hundreds-of-kilowatts class or greater. They both offer high efficiencies (from the teens to more than 20 percent) in their applicable power ranges.

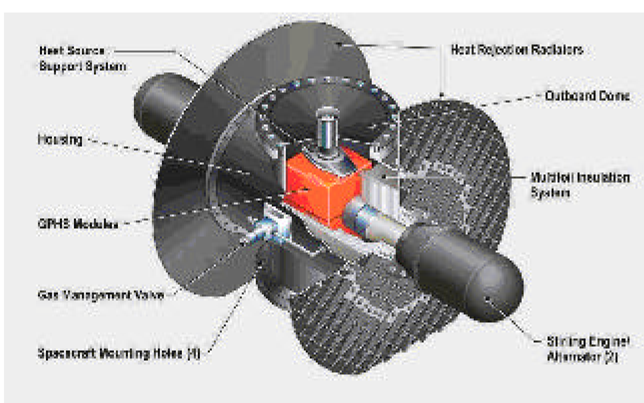


Figure 4.5-3. Conceptual diagram of a 110 W Stirling Power System.

Small planetary surface nuclear power generation systems will be required as precursors to larger systems to be used for eventual human exploration of the planets

Energy Storage

Energy storage systems may be needed for primary power or for operations during some phases or cycles of specific missions when power generation is inadequate (such as nighttime periods, eclipses, low-temperature environments, and so on). The goal is rugged, high-energy density, rechargeable electrochemical energy storage systems to enable planetary orbital and landed solar-powered missions (fig. 4.5-4).

Low-temperature rechargeable batteries capable of operation down to –60 degrees Celsius and that can provide 1,000 cycles are needed for Mars and other planetary surface missions, with stored energy densities near 100 Wh/kg. Planetary orbiters require light weight (> 100 Wh/kg) and compact rechargeable batteries capable of providing more than 30,000 cycles. High-impact low temperature primary batteries capable of operation down to –100 degrees Celsius and capable of operation after hard impact (up to tens of thousands of g's) are needed for penetrators on planetary/small body surfaces. These primary batteries must also be capable of providing more than 300 Wh/kg of specific energy. Regenerative fuel cells are needed for energy storage on the lunar or Mars surface in connection with large solar power generation systems. Such systems, usually in the tens-of-kilowatts range, are considered enabling for initial operating capabilities for permanent human settlement of the Moon and Mars.

Figure 4.5-4. 28 V, 60 Ah Prototype Mars Lander Li-Ion Battery-110 Wh/kg, -20 C operation.

Power and Thermal Management

Power and thermal management system technologies are needed to provide the power electronics and thermal management systems that will enable power system functionality in extreme deep space environments. Low temperature power electronics are needed for the low temperature extremes of deep space and on planetary surfaces. Electronics may be required to function at temperatures below –100 degrees Celsius. High temperature power electronics are needed for the high temperature extremes found near the Sun and on Mercury and Venus. Temperatures may exceed several hundred degrees Celsius. Some deep space missions also require power electronics that can function in high radiation environments. Thermal protection coatings, materials, and devices may be needed for special applications, such as flight near the Sun or atmospheric entry, and electromagnetic shielding for plasma arcing mitigation may also be needed for specific missions.

Deep Space Propulsion

Propulsion has become one of the dominant mass elements of deep space robotic spacecraft as deep space missions are becoming more complex from a propulsion point of view. While robotic spacecraft would once fly past planetary bodies of interest, today's missions seek to rendezvous with, orbit, land on, or even return samples from these bodies. As deep space missions are more ambitious propulsively, the mass of the propulsion system increases as well because the mass of at least part of the "dry" propulsion system is proportional to the mass of the propellant to be consumed. The proportion of the spacecraft that is devoted to propulsion components also increases as electronics systems become more mass efficient. The orders of magnitude increase in avionics capability that has been accompanied by an orders of magnitude decrease in the mass of avionics systems has not only made spacecraft more capable, but these trends have also lowered the dry mass of the spacecraft. This trend is easily seen in the ratio of dry propulsion mass to dry mass of the spacecraft, which has increased from 10 percent for Viking to 11 percent for Galileo in 1989, then to 19 percent for Cassini in 1997 with a projected 38 percent for the Europa Orbiter in 2002.

In 1993, this trend was apparent and was one of the reasons that the NASA Solar Electric Propulsion (SEP) Technology Application Readiness (NSTAR) program to validate ion propulsion for deep space spacecraft was initiated (fig. 4.5-5). By making the advantages offered by an order of magnitude increase in propellant efficiency available to the deep space science community, NSTAR has made possible ambitious missions to primitive bodies as part of the Discovery program.

As we now look ahead to the challenging missions identified for the Deep-Space Systems Technology Plan during the conference at Galveston, Texas, it is clear that greater advances are necessary if frequent missions using small launch vehicles are to be realized. Achieving that vision requires that the dry mass of propulsion systems, as a fraction of the spacecraft's dry mass, not only be held at historical levels but also reduced below those levels as spacecraft become even smaller. Today, the deep space program is faced with several immediate propulsion challenges: chemical propulsion for the Mars Ascent Vehicle, chemical propulsion for Outer Planet spacecraft, and electric propulsion for high Delta-V missions.

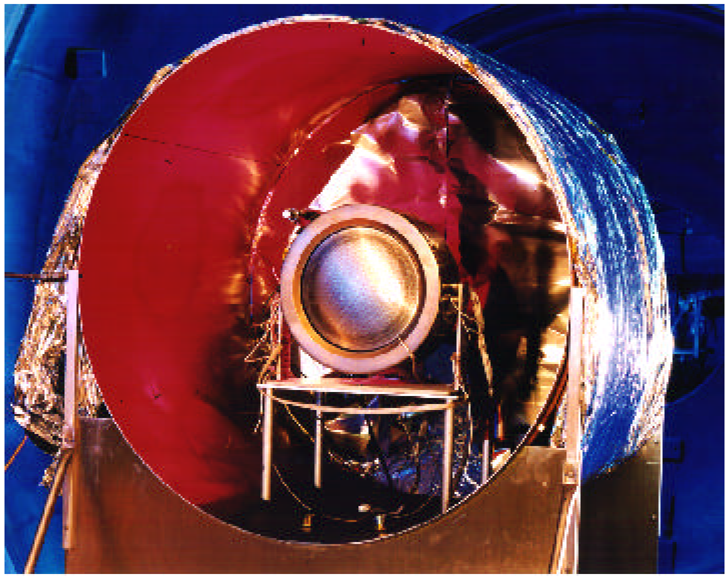


Figure 4.5-5. NSTAR Ion Propulsion Engine undergoing thermal vacuum testing at the Glenn Research Center.

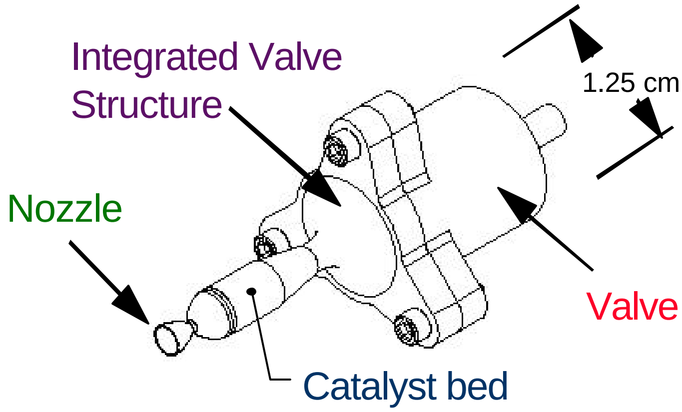
Mars Ascent Vehicle

The Mars Sample Return mission originally planned for 2005 will now be considered a 2011 mission. The limited payload capability of a Delta-III class launch vehicle puts enormous mass pressure on such an ambitious mission. To be successful, the dry mass of the propulsion system to be used on the Mars Ascent Vehicle for this mission must be less than one-half that of the system that could be developed using today's state-of-the-art. In Fiscal year 2001 there is a joint MSFC/JPL Mars Ascent Vehicle Study Team that will be assessing what critical ascent technology is needed and when for a 2011 Mars Sample Return mission. Technologies identified will be funded in the next several years to enable a flight ready approach for the start of the 2011 mission.

Outer Planet Spacecraft

Outer planet spacecraft, such as the Europa Orbiter, the Pluto-Kuiper Express, and the Solar Probe, all face a similar challenge: fitting the spacecraft needed to perform a scientifically and propulsively demanding mission onto a launch vehicle having limited launch mass capability. To meet this challenge, the dry mass of the propulsion system must be reduced by a factor of two from that currently available. This is similar to one of the challenges faced by the propulsion system for the Mars Ascent Vehicle. Because the thrust level for the Mars Ascent Vehicle is much larger than that of the spacecraft for the Outer Planet missions, the components developed either for the Mars or the Outer Planet applications would not be applicable directly to one another, but the design techniques and approaches developed for each would be mutually supportive.

In some instances, the Outer Planet spacecraft require precision pointing and attitude stability that cannot be achieved even with the 0.9-newton attitude control thrusters available today. In the absence of lower force thrusters, these spacecraft could only achieve the precision pointing and stability they require by using reaction wheels, which present a significant mass penalty. The development of a millinewton hydrazine thruster (fig. 4.5-6) has been identified as a way to achieve the desired pointing and stability without incurring a mass penalty the spacecraft design cannot afford.



- Unique approach to flowrate control
- Revolutionary design for thermal control
- Advanced catalyst and catalyst substrate

Figure 4.5-6. Hydrazine millinewton thruster.

JPL has made a significant breakthrough in the area of ultra-lightweight propulsion tanks for deep space missions (fig. 4.5-7). Through use of ultra-thin aluminum liners made by chem milling and a composite overwrap using state-of-the-art PBO fibers/resin, the dry mass of a representative tank (20-inch diameter) was reduced over 60 percent from current available titanium tank technology. Technology development was so successful that recently this ultra-lightweight tank concept has been baselined for use on the MER '03 Project. Two hydrazine tanks will fly on each of two MER spacecraft cruise stages, thereby saving almost 10 kgs in dry mass.

Figure 4.5-7. An ultra-lightweight hydrazine tank.

The magnetic field and rapid rotation rate of Jupiter presents a unique opportunity for the use of tethers as both a power-generating system and a propulsion system. Return visits to the Jovian system could benefit significantly from tethers if the technology necessary for their use is brought to fruition.

Electric Propulsion for High Delta-V Missions

For deep space missions, the high Isp offered by electric propulsion affords significant propellant mass saving for high Delta-V missions. Because of the large variation in solar irradiation experienced in deep space missions, the electric propulsion system that propels these spacecraft must have a large throttling range over which it efficiently operates. In addition, the engines must have a long service life capability to minimize the number of units needed and the system must be able to process large amounts of power to shorten trip times. An ion propulsion system derived from the NSTAR system is needed that offers increased lifetime (measured as total propellant throughput), higher specific impulse for higher Delta V missions, greater low-power efficiency from an improved neutralizer, a lighter weight power processing unit, and a lighter, more efficient propellant storage and control system that allows for the independent control of each flow to the ion engine.

Looking farther into the future, the need for even more mass efficient systems can be seen, particularly as spacecraft become smaller. Improved ion thrusters that offer lower specific masses are needed. Extreme miniaturization with adequate performance and service life capability can only be realized by improved understanding of the fundamental physics of ion thrusters. Eventually, as spacecraft become still smaller, both chemical and electric propulsion systems of the same scale as the microspacecraft they propel will be necessary. Work today investigating MEMS-scale valves, flow controllers, and thrusters (both chemical and electric) is necessary if the propulsion systems of tomorrow will be available for the spacecraft of tomorrow to realize their potential.

If we lift our eyes to a more distant horizon, we see beyond the limits imposed by the solar system and wonder about the new things we will discover when we reach outside the orbit of Pluto to the Kuiper belt, the Oort cloud, and beyond. Such propulsion concepts as very high-powered electric propulsion, antimatter catalyzed fission/fusion, fusion, or beamed energy propulsion are necessary to reach these distances in a reasonable time. When we look still farther, to a time half a century from now when the Origins program has identified star systems with potentially life-supporting planets, propulsion systems that harness a significant fraction of the energy released by matter/antimatter annihilation or capture beamed energy will be necessary for an interstellar probe to reach one of these star systems in a reasonable time. In pursuing such a long-term goal, the enormous scientific yield of precursor missions will be more readily realized.

The propulsion program that will lead to NASA's future and simultaneously address the mid-term needs of NASA's planned missions is composed of both chemical and electric propulsion, of relatively near-term approaches, and of concepts whose feasibility has not yet been demonstrated. Spanning all these concepts, near- and far-term, is the need to reduce propulsion dry mass, which improves the performance of all propulsion approaches.

Advanced Deep Space Communications

The Space Science Enterprise section of the NASA Strategic Plan states that the long-term plan of technology development is to enable a "virtual presence for autonomous scientific discoveries" throughout the solar system. This vision will transform what we currently call deep space communications into an equivalent "solar-system wide area network" providing Internet-like connectivity between scientists and their spacecraft instruments.

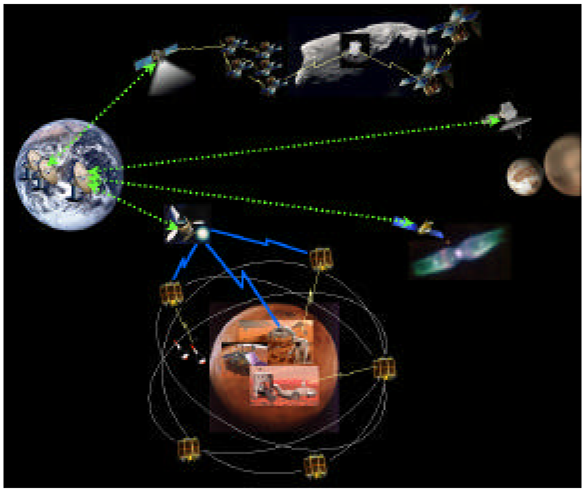


Figure 4.5-8. Deep space communications scenario.

Deep space communications traditionally refers to any communication with or between any spacecraft (orbiter, flyby, observatory, and so on) beyond 2-million kilometers from Earth. Early communications systems supporting exploration of the solar system primarily have been concerned with closing the physical link directly between an Earth ground station and an individual spacecraft at great distance. We are now entering the era where intercommunications among several spacecraft (orbiters and landers) are needed to provide a cost-effective means for scientific investigations. Studies have concluded that the exploration of Mars will be best performed by the establishment of a communications infrastructure, consisting of a dedicated constellation of microsatellites in low orbit as well as more capable relay satellites in stationary orbit as shown in figure 4.5-8. This infrastructure will also provide navigation services. On the presumption that the exploration of space will eventually lead to the need for communication among planets, satellites, asteroids, robotic spacecraft and crewed vehicles, long-term technology plans must put a heavy emphasis on the development of a stable interplanetary backbone network.

From a deep space communications architectural point of view, there are two distinct types of links for this Internet-like connectivity. The first one provides long haul links between spacecraft and the Earth bound Deep Space Network (DSN). At a distance of many millions (even billions) of kilometers from Earth, deep space communications pose unique challenges over the near-Earth communications. This requires aggressive measures on the spacecraft—to radiate as much effective power as possible—and the very special receiving stations of the DSN. For example, the distance-squared factor for a Neptune mission is more than 10 billion times larger than for a geostationary commercial communications satellite. Communications over interstellar distances will be even more challenging. Furthermore, since radio signals are extremely weak when they are arriving at Earth from space, current deep space missions are allocated their own radio frequency bands to minimize interference from terrestrial signals that can be many orders of magnitude stronger. Deep space-specific frequencies also imply equipment that will be different from those used for terrestrial frequencies. These differences in both frequencies and in applicable environments will require, at a minimum, significant modifications to commercial products and, in many cases, whole new designs to achieve the required performance levels.

The second type of communications links is for proximity communications over distances of 10,000 kilometers or less. These links are targeted for in situ instruments (lander, rover, microprobe, and so on), formation flying, or other short-range communications needs. While these short-range systems may use more traditional earthbound frequency bands, they must also operate in the harsh deep space or planetary environment. Temperature extremes can be both very hot and very cold. Radiation effects range from relatively benign to extreme (see figure 4.5-9). Mission lifetimes of 10 years or more are often required just to get to the target bodies, with more time required for the operational science phases. All of these factors stress the design space for the spacecraft communications equipment. Most terrestrial communications equipment is not designed to withstand these extremes. Note that no assumption is made as to whether the mission has a human pilot or is robotic. The technology portfolio covers the full end-to-end link, including all space borne and earthbound assets.

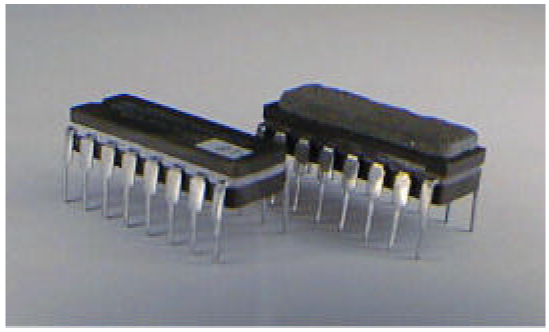


Figure 4.5-9. Radiation-hardened microelectronic communications components.

Furthermore, deep space spacecraft are getting smaller and more highly integrated. Hence, the communications portion must shrink and be very closely tied into the overall spacecraft architecture. This will be particularly true for small space vehicles such as rovers and landers.

For future deep space missions, significant reductions in the mass and power requirements for short-range telecommunication systems will be critical in enabling a wide variety of new mission concepts. These possibilities include penetrators, gliders, miniature rovers, sensor networks, and operations using orbital relays. Under joint funding from NASA’s Cross Enterprise Technology Development Program (CETDP) and JPL’s Telecommunications and Mission Technology programs, recent development activity has focused on the design of ultra low mass and power transceiver systems and subsystems suitable for operation in a flight environment. For these efforts, the functionality of the transceiver has been targeted toward a specific Mars communications scenario. However, the technology is well suited to any short or medium range application where a remote probe will aperiodically communicate with a base station, possibly an orbiter, for the eventual purpose of relaying science information back to Earth.

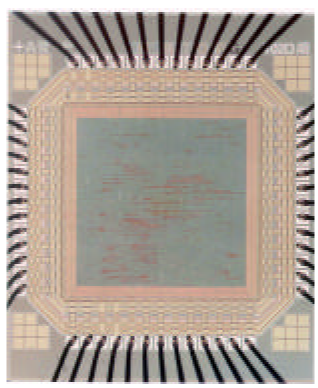


Figure 4.5-10. Ultra low power, digital baseband, FSK Receiver ASIC (0.25 µm CMOS).

Figure 4.5-10 shows the latest multi-rate receiver ASIC designed and fabricated based on commercial CMOS process. A prototype RF front end has also been developed using discrete components to test receiver performance. While the ASIC requires less than 2 mW for operation, the discrete front end consumes far more than the design goal. Consequently, future technology development will be focused on RF integrated circuit (RFIC) design with radiation tolerant or hardened capability, such as Honeywell’s Silicon-on-Insulator CMOS (SOIC). Further evolution of this activity will gradually integrate RF and digital IC designs onto a single ASIC and also merge transmitter and receiver functions. The development of these designs will be performed in a modular fashion to ultimately provide a reservoir of rapidly infusible functions tailored to future short-range communications needs.

Higher Frequency Technologies

Future NASA missions will fly smaller spacecraft with instruments that will generate greater data volumes than current spacecraft. Multispectral imagers synthetic aperture radar (SAR) and high-rate sensors are driving this requirement. Conventional deep-space radio-frequency (RF) communication systems (particularly X-band) will have difficulty meeting these demands due to limited bandwidth allocations, over-subscription of the ground receiver network, and technology limitations. At the same time, the trend toward smaller spacecraft will dictate that the communication system relaying those data be much smaller in size.

Figure 4.5-11 Experimental 7 channel array receiver on top of the XKR cone of the 70 meter antenna in the Deep Space Network.

Deep space communication is moving beyond the currently used X-band (8 GHz) frequencies to Ka-band (32 GHz) and optical frequencies for the spacecraft and ground systems. This move is to take advantage of the physics of shorter wavelengths to decrease aperture sizes and increase the capacity of the Deep Space Network to handle the predicted larger number of future missions. The challenge is to develop not only the equipment to utilize these new frequency bands, but also the operational techniques and methodologies to handle weather and atmospheric effects (such as diversity, adaptive signal processing, adaptive optics, and adaptive resource scheduling).

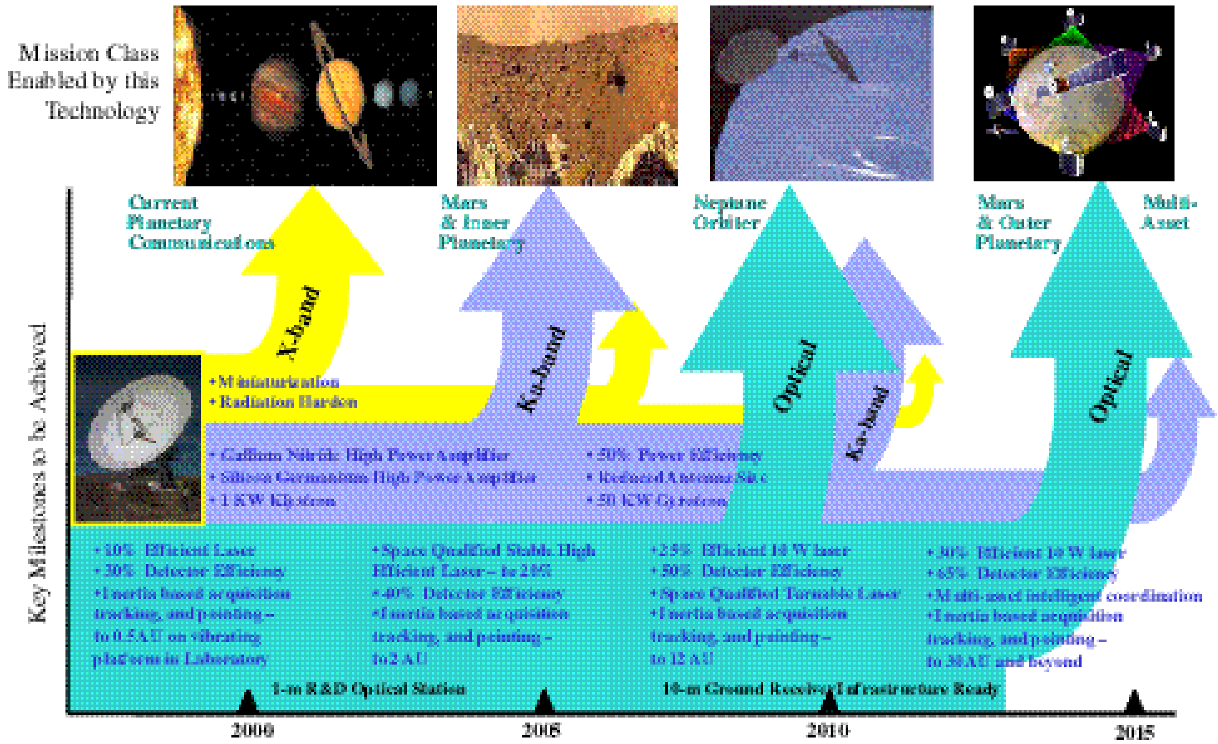


Figure 4.5-13 Technology roadmap for deep space communications.

Ka-band Communications. Near-term mission enhancements will be available by using Ka-band communications. Factors of four increases in link capacity can be achieved with current technologies and factors of ten are on the horizon. Numerous flight demonstrations have been conducted with Ka-band frequencies including modest demonstrations from SURFSAT, Mars Observer, and Mars Global Surveyor, and a complete Ka-band demonstration was conducted from the DS1 spacecraft. Recent experiments have demonstrated the feasibility of receiving Ka-band transmissions from the Cassini spacecraft using DSN antennas with phased array feeds (fig. 4.5-11). Several other technologies are currently being developed to enhance the capabilities of future Ka-band systems. These include large inflatable antennas (fig. 4.5-12) and higher-powered Ka-band power amplifiers using the latest solid-state material (such as GaN and SiGe) for fabrication.

Additionally, work is underway to develop the ground systems technologies required to support Ka-band reception. These include multi-frequency dichroic plates, low-noise Ka-band maser and HEMT amplifiers, and compensation systems to allow the DSN's antennas to be efficiently used at Ka-band. Figure 4.5-13 summarizes the technology development.

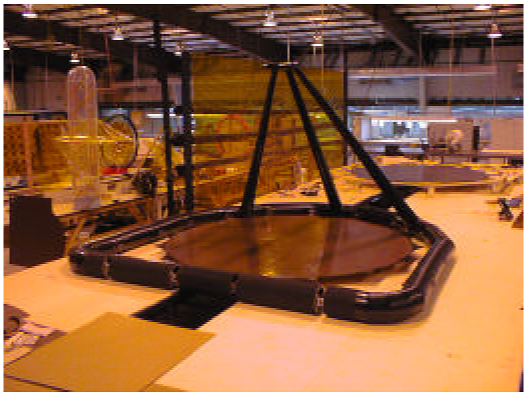


Figure 4.5-12 3-m diameter inflatable Ka-band antenna.

Optical Communications**.** Free-space optical communications is an emerging technology under development for addressing increased communication capacity and reduced size requirements. It is seen as the technology that will enable future near-Earth, solar system, and interstellar missions. The potential of delivering as much as 10 times higher data-rate with 10 times reduced size and lower mass, relative to the conventional spacecraft communication technology (assuming the same input DC power), makes this technology attractive.

The technical merit of laser communications is derived from the fact that it offers a more concentrated signal than conventional microwave. This super-collimated beam can result in a terminal design with greatly reduced size, mass, and power requirements. Furthermore, laser communication systems are not susceptible to RF interference and are currently not subject to government or international regulations. Additionally, the higher data return rates afforded by optical communications reduce the required ground coverage time that is needed to recover the science data. This also reduces ground operations cost.

NASA has been actively pursuing the development of this technology for future space missions to provide higher data volume return to meet increasing demand. In 1992, JPL performed the first optical pointing experiment at the Table Mountain Facility in Wrightwood, California, when the Galileo spacecraft receded from Earth during the gravitational assist fly-by. The experiment validates the narrow beam pointing capability necessary for deep space optical communications at a distance from 600,000 km to 6-million km over a period of seven days. The first two-way optical experiment was conducted by JPL in 1996 from the same facility to a near geo-synchronous orbit satellite. Furthermore, JPL, in conjunction with industry, also plans to develop the technology of a deep space optical communications transceiver for mini-spacecraft that would support tens of Kbps data-rate from the Mars range using a 1-W laser transmitter and a 10-cm aperture. This is an order of magnitude improvement over the current RF systems.

In 1996 JPL began the development of a flight terminal engineering model called the Optical Communications Demonstrator (OCD). The OCD has recently been used in field tests across a 46 km long mountain top-to-mountain top demonstration. An Optical Communications Telescope Laboratory (OCTL) is also currently being installed at JPL's Table Mountain Facility. This will be used to validate optical technologies and systems designs, and to support a series of near-term flight demonstrations. Additionally, JPL has developed and deployed a set of three Atmospheric Visibility Monitoring observatories for gathering space-ground atmospheric attenuation statistics.

The inherent advantage of optical communications over RF communication systems is the narrower transmitted beam width at optical frequencies. This narrower beam width results in concentrated intensity delivered to the ground receiver. However, the narrower transmit beam width imposes a major technical challenge for pointing the transmitter. To succeed, the optical transceiver must be capable of deducing the receiving station location and maintain pointing of the signal to an accuracy that is small compared to the transmit beam width. The acquisition, tracking, and pointing (ATP) functions are the most important aspect of optical communications since the required pointing accuracy is orders of magnitude tighter than the RF communications and might well be tighter than the magnitude of spacecraft vibration and dead band motion

The implementation of the state-of-the-art ATP involves many aspects of the technology developments including components, concepts, and improvements of the existing systems. The design of an efficient ATP system starts from identifying the pointing error sources that need to be minimized by ATP functions. Among various pointing error sources, the spacecraft platform vibration is the most dominant error source. The most effective method to achieve maximum compensation for vibration is to increase the bandwidth of tracking control loop with either optical tracking or inertial sensor tracking. Since optical tracking is limited in deep space due to lack of bright target reference sources, the role of the inertial sensor increases. The emphasis in developing inertial sensors should be on the accuracy and stability of the sensor. Another critical element of tracking control loop is the fine steering mirror that must have large bandwidth to realize the large control bandwidth. The second major error contributor is the measurement of beacon position on FPA due to read noise and Analog-to-Digital Conversion quantization noise. Tracking strategy will become more complicated in integrating multiple sensors and concepts.

Future technology development in this area will focus on improving efficiencies on lasers and detectors for space qualifications as well as developing inertia based ATP system from 2 AU to 30 AU and beyond. Today these technologies are in infancy stages for deep space communications. Due to unique communications requirements for deep space applications, military technologies for satellite crosslink and near-Earth downlink are not directly applicable. Near-Earth optical communications focus on multiple Gbps transmissions with high average power lasers while the deep space optical counterpart requires extremely high peak power concentrated in nano seconds with orders of magnitude lower average power. Figure 4.5-13 summarizes the technology development for deep space missions related to X-band, Ka-band, and optical frequencies.

Integrated Technologies

The components of deep space communications systems must be closely integrated. This is particularly true of the short-range communications needs of in situ systems that may be heavily constrained in power and volume. Telecom-on-a-chip and micro electrical-mechanical front-ends are two examples. Furthermore, as the evolutionary advancement of solar system exploration increases the multiplicity of in situ assets, the interconnectivity among these communicating entities in deep space becomes more sophisticated. This introduces the need for advanced communications protocols capable of self-organizing the network and adapting in real time to local conditions and potential faults. At the same time, development of mission science and engineering software applications benefit from using well-known standard APIs to communications services, such as those used for distributed computing over the Internet. Design of the latest Proximity-1 draft standard is representative of progress being achieved in developing protocols that can provide transparency to user applications while autonomously accommodating the dynamics and efficiencies demanded of operating networks in deep space environments.

The development of communications technology must be also closely coordinated with the development of other systems onboard the spacecraft, such as the attitude control for antenna (optical or radio frequency) pointing and avionics for onboard data handling. In the future, we may see instruments integrated with communications functions such as a telescope serving both as part of an imaging system and an optical communications receiver/transmitter. The communications protocol will also be an integrated part of any autonomy efforts on the ground or the spacecraft.

None of these technologies can be developed in a vacuum. End-to-end systems analysis to ascertain the appropriate trade of spacecraft and ground resources, as well as operational coordination and economies, is fundamental to providing direction to the technology development (fig. 4.5-14).

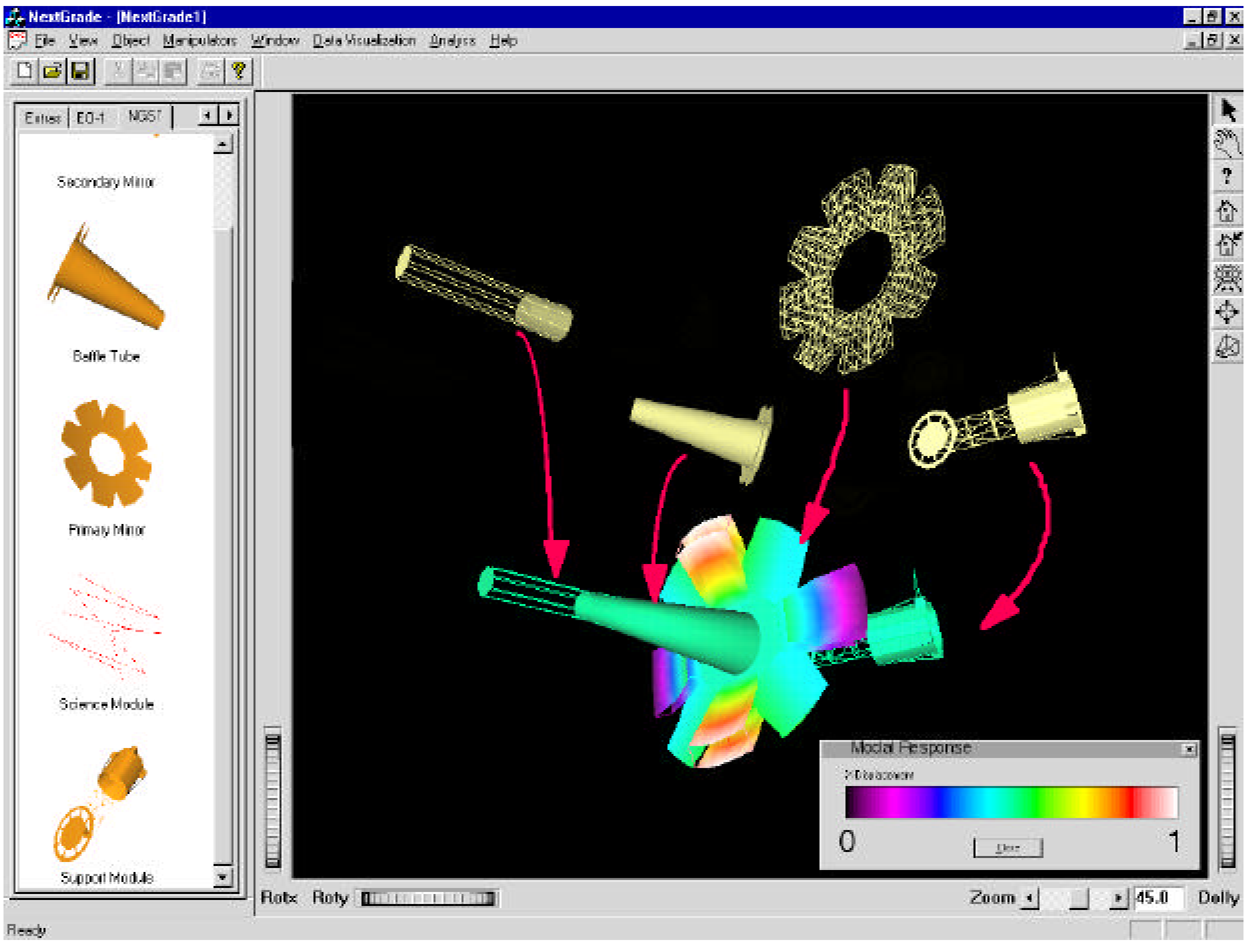


Figure 4.5-14. Example of system analysis tools for a next generation space telescope.

The program will leverage the activities of the commercial communications industry as much as possible. It will form strategic partnerships with industry and academia to get the "best and brightest" as well as address the deep space unique nature of our developments.

Autonomy Technology

The future exploration of space will require highly capable spacecraft that can respond intelligently to unexpected events, avoid hazards, seek out science opportunities, and recover robustly from faults—all with limited human intervention. These autonomous explorers will enable exciting new missions to previously unexplored environments where unpredictable events and light-time delayed communication make direct human control infeasible. Greater spacecraft autonomy is also needed to reduce mission operations costs, and enable cost-effective control of multiple-spacecraft missions. Advances in several computing technologies are needed to enable these intelligent systems, including the following:

Autonomous planning and execution technologies that reduce operations costs and enable robust achievement of mission objectives in the face of dynamic and uncertain environments.

Distributed autonomy for coordinated control of spacecraft constellations and rover fleets.

Health management software that detects and diagnoses faults in complex systems.

Machine-vision systems for precision landing and hazard avoidance.

Software that can recognize scientific events and features in instrument data. This enables analysis of vast data sets and, in conjunction with automated planning and execution technologies, enables automated detection and exploitation of science opportunities.

Verification and validation technologies that ensure reliable autonomous systems.

Quantum computing algorithms and hardware. These super-fast computers, now in their infancy, could enable breakthrough improvements in the reasoning power of autonomous systems.

Looking farther into the future, autonomy will be an enabling technology for visionary missions such as submarine exploration of the predicted oceans beneath the icy crust of Europa, colonies of intelligent collaborating robots on Mars, and sustained-presence missions that require spacecraft to survive and seek out science opportunities over long periods with minimal intervention.

Mission Planning and Execution

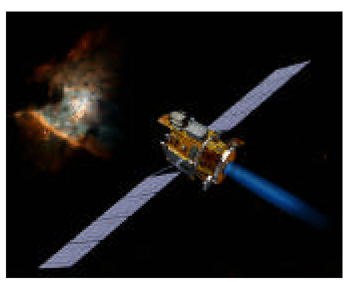


Figure 4.5-15 Deep Space 1

This thrust area develops intelligent planning and execution technologies that enable spacecraft to be commanded with high-level goals rather than detailed sequences. These capabilities reduce operations costs and enable robust operations in dynamic and uncertain environments. The spacecraft possesses, in onboard software, the knowledge and reasoning procedures for determining the actions needed to achieve those goals while preserving spacecraft health. The spacecraft continually monitors itself and its environment, and changes its course of action as needed to achieve its goals. The state-of-the-art in this area is the Remote Agent, which autonomously commanded the active cruise phase of the DS1 spacecraft for several days (fig. 4.5-15). Operations in more challenging environments will require improvements in reaction speed, robustness, and plan quality. Current research in this direction includes integrated planning and execution architectures, continuous planning algorithms with shorter reaction times, and planning for contingencies.

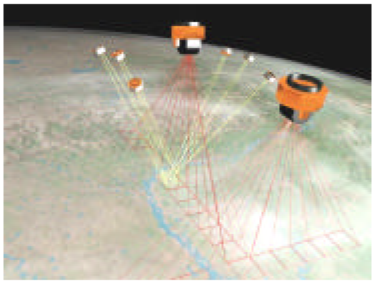


Figure 4.5-16 A constellation mission concept (LEONARDO).

Distributed Autonomous Systems

Future NASA missions will involve multiple spacecraft or rovers that must interact with one other to achieve their mission goals (fig. 4.5-16). Commanding a constellation by issuing individual sequences to each spacecraft would be cumbersome, expensive, and unlikely to achieve coordinated action in a dynamic or uncertain environment. New autonomy technologies are needed that can operate a constellation as a coordinated entity by issuing collective mission goals instead of individual command sequences. Current approaches to spacecraft planning, scheduling, and control must be extended to enable robust operation of multiple spacecraft.

Autonomous Guidance and Control

Figure 4.5-17 Artist's depiction of an asteroid exploration mission.

Exploration of solar system surfaces requires robotic systems that can navigate, land, and avoid hazards (fig. 4.5-17). This requires onboard intelligence that can quickly assess the situation and react to changing events. This thrust area is developing autonomous guidance and control technologies with these capabilities. Technologies currently under development include machine-vision algorithms for precision landing and hazard avoidance on small bodies.

Science-Data Understanding

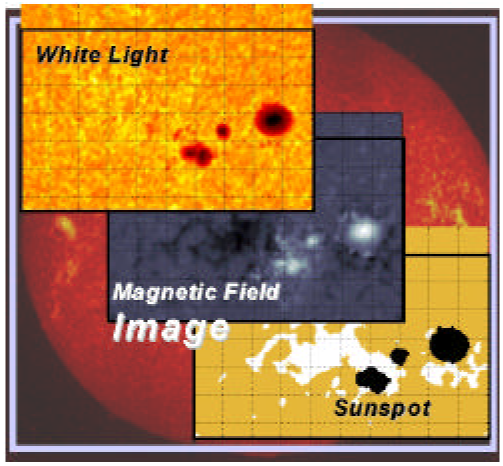


Figure 4.5-18 Startool, a trainable sunspot recognizer.

This thrust area develops systems that automatically identify scientific events in instrument data. Technologies currently under development in this area include trainable sunspot recognizers (fig. 4.5-18), detectors for craters and volcanoes, and systems that find natural satellites of asteroids. As a part of ground-based systems, these technologies enable scientists to automatically mine vast spacecraft data volumes for the information they need. Combined with onboard planning and execution technologies they enable the scientists to prioritize and summarize data onboard, to scan high-rate data streams for short-lived or hard-to-find events, and to detect and exploit fast-breaking science opportunities such as eruptions or solar flares that would otherwise be lost.

Advanced Computing and Software Engineering

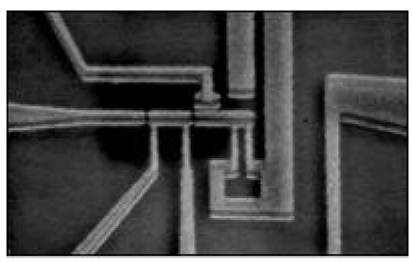


Figure 4.5-19 Quantum logic gate

Autonomous systems are highly complex and operate in mission-critical environments. Advances in software engineering and validation are needed to minimize development costs and ensure high reliability. These include research into autonomy architecture design, validation of model-based systems, and unified knowledge-engineering languages. Autonomy software often involves computationally expensive algorithms. Advances in quantum computing and biologically inspired computing are needed to produce computers that can solve currently intractable problems. This could provide breakthrough improvements in the response time and reasoning power of autonomous systems. Near-term investigation is focused on fundamental theory and algorithms and circuits for quantum computing (fig. 4.5-19), leading to development of quantum computing hardware in the mid- to far-term.

Deep Space Robotics Technology

Cutting-edge planetary robotics technologies are needed for a wide range of deep space missions to solar system surfaces. These missions will investigate and characterize planets, comets, and asteroid surfaces, as well as penetrate subsurfaces and atmospheres with new robotic systems. The deep space robotics technology program creates, evaluates, and demonstrates first-of-a-kind integrated research and technology robots, in which several critical technologies are developed together to provide new system-level deep space robotics operations to mission scientists and designers. Enabling robotics technologies under development include

- miniaturized long-range science rovers for long-range autonomous traverse on planetary surfaces and for deploying, pointing, and operating multiple science instruments from a mobile vehicle
- fast, stowable sample return rovers to locate, recognize, pick up, and retrieve preexisting sample caches quickly and reliably deliver them to an awaiting Earth return vehicle, embedding unique technological advances in mechanical and thermal design using composites, local area guidance, visual object recognition, and mobility control
- nan rover vehicles that achieve breakthroughs in size reduction, mobility, and science return through synergistic technological advances in ultra-miniaturization
- smartly controlled micromanipulators and drilling and coring robots to acquire soil and rock samples, to inspect and handle, and to perform precise trenching, scooping, and sample containerization in deep space planetary surface missions
- subsurface explorer robots for deep penetration and in situ soil composition and chemical analysis, maneuvering in the expected regolith (for example, soil and permafrost) of planetary bodies such as Mars or comets

In response to challenges on the more distant horizon, robots capable of autonomous reconfiguration for all terrain navigation, and for multi-robot cooperative operations within robotic outposts, are research and development topics of intense interest. Robotic outposts are relatively new mission concepts that aim to establish a permanent robotic presence on planetary surfaces, to conduct extensive science operations using multiple surface robots, and to pave the way for eventual human presence by the robotic deployment and assembly of the infrastructure necessary for subsequent human missions. They also include “sensor-web” technology investigations that are concurrently applicable to exploring our own planet and other planetary surfaces.

Deep Space Robotics Technology: High-Risk Access Systems

This theme area develops smarter, faster, and more maneuverable rovers and other types of robotic surface systems. This includes unique mobility robotic mechanisms to do such risky tasks as descending cliffs and craters, as well as multi-mode hybrid aerial and surface systems to provide wide area coverage and traverse extremely rugged territory (fig.4.5-20).

Figure 4.5-20 Inflatable rover technology.

Deep Space Robotics Technology: Robotics Outposts and Colonies

This theme area focuses on multiple cooperating robots forming autonomous robotic surface system colonies for in situ surface measurement and communications and to pave the way for human exploration of planetary surfaces. It encompasses multi-robot control architectures for robot coordination, as well as self-sustaining robotic systems to achieve permanent and even perpetual presence by means of such technologies as autonomous robotic repair systemsfig. 4.5-21).

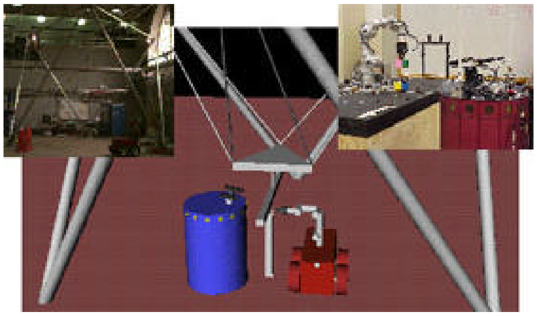


Figure 4.5-21. Distributed multirobot control experimental tests.

Deep Space Robotics Technology: Deep Sub-Surface Systems

This theme area develops techniques for subsurface sampling of planets and comets at tens of meters depth and more, including drills and moles as well as ice penetrating robotic probes (fig. 4.5-22).

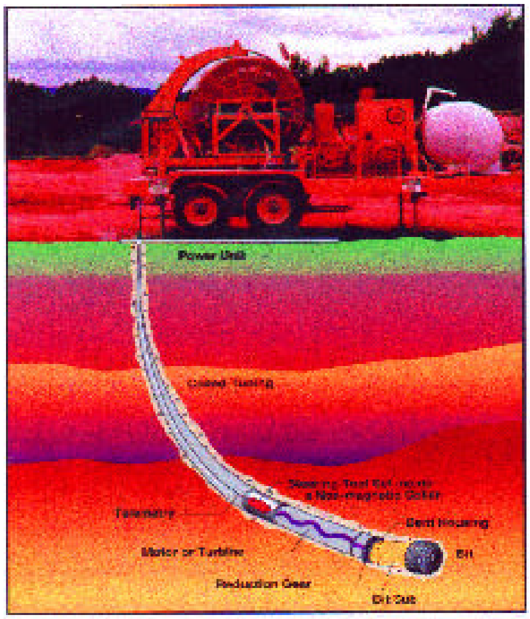


Figure 4.5-22. Deep subsurface research.

Deep Space Robotics Systems: Hybrid Human and Robot Systems

This theme area focuses on robotic assistance to surface EVA to perform tasks that are more easily done by robots under supervisory human control, and on technology to allow humans and robots to work together in achieving complex (e.g., repair) tasks (fig. 4.5-23).

Figure 4.5-23. Exploring a unique set of kinematic and kinesthetic constraints on interaction with robotic agents.

Deep Space Robotics Technology: Sample Acquisition and Processing Systems

This theme area develops techniques for in situ handling and sample acquisition, sample storage and transport, and Earth returned sample curation and handling (fig. 4.5-24).

Figure 4.5-24. Development of special handling for samples returned from other solar system bodies.

Deep Space Robotics Technology: In Situ Resource Utilization Systems

This theme area develops robotics systems that use in situ resources, and balance their energy usage and generation, in order to achieve mission goals with minimal transport of energy and other resources from Earth. These deep space robotic systems enable science and human missions not possible without ISRU (e.g., hoppers, pneumatic equipment, long-term science gases, etc.).

The technology roadmap for these areas is summarized in the following table:

TABLE 4.5-1. Long Range Technology Forecast for Deep Space Robotics Systems Thrust

PBS Element	Now	5 Yrs	10 Yrs	>15 Yrs
High-Risk Access Systems Mobility and Navigation	Wheeled Rovers 100s Meters; Supervised Autonomy; Conventional Terrain	Multi-Mode Mobility (hop,fly,etc); > 100 km Regional Autonomy; All Terrain Capability; Cliff Ascent/Descent	> 1000 km Multi-Mode Mobility Surface Coverage; Coordinated Communications; Unattended Autonomy	High-Resolution Global Surface Coverage; Precision Access and InSitu Probe
Robotic Outposts and Colonies	< 10 Sojourner-Class Rover Surveys Local Area in Coordination with Landers; Daily Earth Communications	Low-Cost Robot Teams; Wide Area Measurement and Communication Nets; Weekly Hands-Off Operations	> 10 Yrs Self-Sustaining Systems; Robotic Repair and Maintain; Monthly Hands-Off Operations; Team Work	Permanent /Perpetual Presence in Deep Space Robotic Infrastructures; Long Duration Autonomy
Deep Sub-Surface Systems	10s of Samples in Low-Depth Coring Devices	< 10 meter in Mars regolith by percussive robot systems; Icy Media Robotic Penetrator Proof-of-Principle Experiments	> 100 m Access to Samples in Mars Regolith	Active Thermal Probe for Icy Planetary Environments
Hybrid Human and Robot Teams	Rovers Do Full Sample-Acquire Cycle with 1 Ground Command	Collective Autonomy of < 10 Robots Commanded from Earth	Remote Robotic Assistance to Earth-Based Science Analysis	Robot Crews Help Humans in Surface Science Operations
Sample Acquisition and Processing Systems	Small robot arms for surface sampling (e.g., Athena 03, 05)	Automated Extraction of Volatiles (H,C,N,H20) from Mars Regolith; Returned Sample Handling	Multi-Site Land, Ascent, and Sampling Robotic Systems (10s of sites)	Anchor, Sample and Retrieve Robotic Systems for Irregular and Poorly Known Media (Asteroids and Commets)
In Situ Resource Utilization Systems	Propellant production breadboards and precursor experiment	Base technology for ISPP flight demos; consumable production breadboards (fuel cell reagent, science instruments, etc.)	ISPP-fueled ascent vehicles, hoppers and rovers; micro-g soil processing and collection; subsurface resource collection & processing	ISPP based robotic and human outposts; ISPP based comet, moon, and asteroid exploration and sample return; asteroid/moon processing for science and human structures

The deep space robotics systems technology under development has long range objectives that are quite challenging and will lead to revolutionary capabilities. Many of the technologies needing development are in their infancy.

- multiple, coordinated multi-scale (small and large) special robots forming networks
- remote robotic work systems (deploy habitats, drill, maintain other robots)
- extend lifetime and power performance envelopes by orders of magnitude
- local robotic outpost communication architectures and systems; high-rate surface switching and aggregation centers and/or aero-synchronous network relays
- manufacture of propellants, oxygen, water, and other resources

Evolution of the technology and infusion into flight systems will require major achievements from the community of researchers involved, and this effort will be quite interesting and exciting over the next decades.

Other Advanced Deep Space Technologies

- In addition to the technology program areas already mentioned, other technologies may play critical roles in specific mission applications. These would include the following examples:
- Lightweight "plumbing" should exist—that is, the size and weight of amplifiers and radios are being reduced to the point where the "stuff" that connects them together will become a dominant factor.
- Lightweight optics and telescopes should be thermally stable over wide temperature ranges (such as silicon carbon and other new materials).
- Error correction coding systems and algorithms for both the radio frequency and optical channels should push performance toward the fundamental channel capacity limits.
- Low-noise temperature, large-aperture ground or orbiting receiving systems (radio and optical), Ultra stable frequency sources for space and ground.
- Technologies for aerocapture and aeromaneuvering, such as advanced thermal materials/ thermophotovoltaics, entry guidance, navigation, and control, and aerothermodynamics models.
- Advanced thin-film materials for extended use in inflatable and other large membrane structures.
- Environmentally hardened structures, coatings, and materials for extended use in high-radiation or severe planetary surface environments.
- Advanced integrated thermal technologies, both active and passive, for spacecraft thermal control in near-Sun, extreme deep space, and planetary surface environments.
- Technologies for extended deep space autonomous operation of remote constellations or fleets of spacecraft and for ultra precision formation control.

- Advanced architectures or systems technology specific to deep space missions.
- Technologies for the exploration and scientific discovery of planetary systems around near by stars, keeping in mind that the drivers for technology investments in interstellar flight are first new propulsion systems followed by revolutionary advances in communications, power, and spacecraft long-life survivable avionics.